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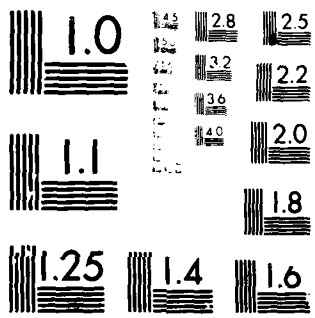

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UTILITY-BORNE COSTS OF THERMAL STANDARDS FOR THE MISSISSIPPI AND MISSOURI RIVERS IN THE MAPP GEOGRAPHICAL AREA

by

A. R. Giaquinta

R. A. Woodhouse

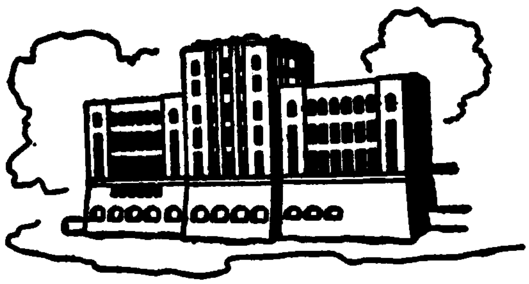
and

M. P. Cherian

Sponsored by

Mid-Continent Area Power Pool (MAPP)

Minneapolis, Minnesota 55402



IIHR Report No. 223

Iowa Institute of Hydraulic Research

The University of Iowa

Iowa City, Iowa 52242

September 1979

ADDENDUM

UTILITY-BORNE COSTS OF THERMAL STANDARDS FOR THE MISSISSIPPI AND MISSOURI RIVERS IN THE MAPP GEOGRAPHICAL AREA

by

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This addendum was prepared to elucidate certain points that were found during the proof stage to require clarification, as follows:

1. p. 19. Fixed-charge rates of 17.90 percent and 14.75 percent were used in the economic analysis of existing and proposed power plants, respectively.
2. p. 25. All of the power plants considered in this study are, or will be, located along major rivers; therefore, hybrid cooling systems were adopted for those cases in which the river heat-assimilation capacities were found to be inadequate to assume the entire waste-heat load when the plant is operated in the once-through cooling mode. It is recognized that few, if any, hybrid cooling systems have been utilized to date. However, rapidly increasing fuel costs and the results of other recent studies suggest that hybrid cooling systems will become steadily more attractive. These systems enable one to utilize the available heat-assimilation capacity of the river, with the result that smaller cooling-tower systems are required. Moreover, during major parts of the year it may not be necessary to operate the towers at all, which can result in further significant savings of replacement energy and maintenance costs.

3. p. 26. Hybrid cooling-system costs were calculated in the following manner: The capital costs were assumed to vary linearly between the costs incurred for once-through cooling and those for full closed-cyle cooling with the wet cooling towers. The hybrid cooling-system capital costs were then calculated from the following equation.

(hybrid-system capital costs) = (once-through capital costs) + [(closed-cycle capital costs) - (once-through capital costs)] x [(heat-assimilation requirement) - river heat-assimilation capacity)] ÷ heat-assimilation requirement.

The capital-cost calculations were made for the 7-day, 10-year low flow conditions. Operating costs were computed as described above, except that they were based on the allowable river heat-assimilation capacity for average-flow conditions.

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UTILITY-BORNE COSTS OF THERMAL STANDARDS FOR THE MISSISSIPPI AND MISSOURI RIVERS IN THE MAPP GEOGRAPHICAL AREA

by

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A. R. Giaquinta

R. A. Woodhouse

[redacted]

M. P. Cherian

Sponsored by

Mid-Continent Area Power Pool (MAPP)
Minneapolis, Minnesota 55402

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Iowa Institute of Hydraulic Research
The University of Iowa
Iowa City, Iowa 52242

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The cooperation of the MAPP-member utilities and the MAPP Coordination Center in providing power plant data is gratefully acknowledged.

The contribution of Professor Thomas E. Croley II, and the advice of Professor John F. Kennedy throughout the study are gratefully acknowledged.

ABSTRACT

Power plant cooling costs and water consumption (evaporative loss) for various river temperature standards are presented for existing and proposed power plants located along the Missouri and Upper Mississippi Rivers in the MAPP geographical area. Thermodynamic and economic models are combined to evaluate the cooling-related costs of river thermal standards. The existing thermal standards and a number of other hypothetical thermal regulations including the extreme cases of no thermal standards and no allowable heated discharges are examined to show the dependence of power-production-related cooling costs and water consumption on thermal standards. A critical appraisal of the cost of thermal standards in terms of water consumption and other costs is thereby possible so that subjective assessments of the standards can proceed with full knowledge of the trade-offs involved between the costs of power production and environmental impacts.

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SUMMARY AND CONCLUSIONS

The use of cooling water from the Missouri and Mississippi Rivers has come under sharp scrutiny in recent years because of possible environmental ramifications. All states through which the rivers pass have instituted river temperature standards constraining thermal discharges that might adversely impact on the river environment. However, the standards were aimed at environmental enhancement with little consideration of the resultant cost to society.

The purpose of this study is to evaluate for the Mid-Continent Area Power Pool (MAPP) geographical area marginal (incremental) changes in cooling-related water consumption (evaporative water loss) and power plant cooling expenses which result from unit changes in river temperature standards along the Upper Mississippi and Missouri Rivers. The theoretical technique used in calculating these marginal changes assumes that all existing and proposed future (through 1987) plants located along the river reaches studied are in operation. The critical assessment of the "worth" of thermal standards in terms of water consumption and power plant cooling costs is thereby enabled so that the subjective assessments can proceed with full knowledge of the trade-offs.

The computational scheme to evaluate the costs of various thermal standards requires the use of the Iowa Thermal Regime Model (ITRM). This model which determines the steady-state river temperature distribution for various external heat loads, meteorologic, and hydrologic conditions is used to locate regions where river temperatures exceed allowable limits for any prescribed set of thermal standards, and to assess river evaporation consequent with those standards.

The economic models include the Backfitting and the Outfitting Models. The Backfitting Model evaluates costs (the term "costs" refers to cooling-related costs throughout this report) of backfitting existing power plants (if needed) with mechanical draft wet cooling towers, and the Outfitting Model computes the cost of outfitting proposed power plants with once-through or mechanical draft wet cooling tower systems.

A number of hypothetical river thermal standards are considered including the extreme cases of free-discharge or no thermal standards and no allowable thermal discharges. The costs of existing thermal standards are assessed by computing the marginal increases in momentary expenditure and water consumption over the free-discharge case. The additional costs (over the free-discharge case) of more restrictive thermal standards also are computed for a complete realization of the impact of these standards.

It is assumed throughout this study that power plants operate at an 80 percent capacity factor. To determine the sensitivity of water consumption and costs to capacity factor, an alternate capacity factor of 70 percent also is considered.

All cost figures are computed in 1977 dollars. It is extremely important to realize that these costs are illustrative only, since fixed unit costs are assumed across-the-board for all utilities along the study reaches, and fixed assumptions are made for the operation of all plants. The numbers cannot be taken as indicative of true costs of any one utility but serve to indicate the generalized total costs for the study regions.

The principal findings derived from the investigation may be summarized as follows:

1. For the study reach of the Mississippi River, the total annual cooling-related costs of power production for the free-discharge, the existing, and the no-discharge thermal standards are about 755, 909, and 1003 million dollars, respectively. The incremental annual costs of the existing and the no-discharge thermal standards (over the free-discharge case) are, therefore, 154 and 248 million dollars, respectively. Incremental unit costs for the existing and no-discharge standards are about 1.8 and 2.9 mills/kW-hr, respectively. For thermal standards intermediate between the existing and the no-discharge case, the costs increase gradually as the thermal standard becomes more restrictive.

2. Total annual water volumes consumed along the study reach of the Mississippi River for the free-discharge, existing, and no-discharge cases are about 106, 129, and 148 million m^3, respectively. The marginal increases

in water consumption over the free-discharge case for the existing and no-discharge thermal standards are, therefore, 23 and 42 million m^3, respectively.

3. Along the study reach of the Missouri River, the total annual cooling-related costs of power production for the free discharge, the existing, and the no-discharge cases are about 428, 447, and 552 million dollars, respectively. The incremental annual costs of the existing and no-discharge standards over the free-discharge standard are, therefore, 19 and 124 million dollars respectively. Incremental unit costs for the existing and no-discharge standards are about 0.45 and 2.9 mills/kW-hr, respectively.

4. Total annual water volumes consumed along the study reach of the Missouri River for the free-discharge, existing, and no-discharge standards are about 61, 61, and 68 million m^3, respectively. Since all power plants along the Missouri River use once-through cooling at existing standards, water consumption for the existing standard is the same as for free-discharge. The no-discharge standard increases annual water consumption by 7 million m^3.

5. Thermal standards also produce additional "costs" in terms of energy losses. The amount of annual energy loss that occurs at the existing and no-discharge thermal standards on the Upper Mississippi River are 1,133 and 2,140 million kW-hrs, respectively. Along the Missouri River, the total annual energy loss for the no-discharge standard is about 1,040 million kW-hrs.

6. The major benefit of relaxing existing thermal standards is that more cooling, and therefore more generation capacity, could be obtained at all locations along a river. For permissible future plant sites along the Upper Mississippi River, the total increases in capacity (in addition to that of existing and future proposed plants) obtained by relaxing thermal standards by 2°F and 4°F increments above the existing allowable temperature

rise are about 9,000 MW and 19,500 MW, respectively. The increases in generation capacity obtained by relaxing existing thermal standards along the Missouri River by 2°F and 4°F increments are about 7,400 MW and 14,800 MW, respectively.

7. A decrease in capacity factor from 80 to 70 percent causes an increase in annual costs (in mills/kW-hr) of about 1 percent and a decrease in annual water consumption of about 12 percent along both rivers.

These results indicate that the establishment of new, or the anticipated revision of old, thermal standards should be considered carefully. Since the regulation of thermal effluents has such a strong influence on steam-electric power plant operation, it is important to realize not only the environmental ramifications of thermal standards, but also their effects on power plant efficiency and usage of natural resources.

In general, more stringent standards lead to higher capital expenditure, fuel consumption, and water consumption. Therefore, thermal standards should be considered in terms of costs vs. benefits or the trade-offs between different levels of environmental protection and their costs to the public.

I. INTRODUCTION

A. Thermal Standards. The demand for electrical energy in the United States is projected to increase at an annual rate of 3.2 percent between 1975 and the year 2000. This rate of increase will more than double today's energy demand by the year 2000 (Searle 1978). To meet this increasing energy requirement, fossil and nuclear power plants of large (1000 MW) capacity presently are being planned or installed by many utilities. Table 1 summarizes data on existing and presently proposed future power plants along the Missouri and Upper Mississippi Rivers in the Mid-Continent Area Power Pool (MAPP). The low thermal efficiencies of these plants necessitate the rejection of large amounts of waste heat from their generating units to the surroundings. The heat rejection is achieved by transferring the waste heat in the condensers to the cooling water. The heat eventually is transferred from the cooling water to the atmosphere, either directly by means of a cooling tower or spray canal, or indirectly through a cooling pond, river, or large body of water.

Once-through cooling has the lowest water consumption (i.e., evaporative water loss) of any evaporative cooling system (although water use is greatest, virtually all is returned to the river). A summary of water consumption of different cooling systems is given by the Environmental Protection Agency (1974). However, the use of cooling water in a once-through mode from the Missouri and Mississippi Rivers has come under sharp scrutiny in recent years because of possible environmental ramifications. All states through which the rivers pass have adopted river temperature standards, which are enforced by federal and state agencies, aimed at constraining thermal discharges that might have an adverse impact on the river environment.

A joint meeting of state and federal governmental agencies on Mississippi River temperature standards was held in St. Louis, Missouri, on March 3, 1971 (Environmental Protection Agency 1971). The report from this meeting recommended that the maximum "artificial" rise in water temperature should not exceed a prescribed limit above the recorded "natural" temperature, nor should the actual temperature exceed the maximum safe temperature, whichever constraint dominates. It was decided at this meeting that power plants

TABLE 1

EXISTING AND PROPOSED TOTAL PLANT CAPACITIES
IN MW ALONG MISSOURI AND UPPER MISSISSIPPI RIVERS

River and Type of Cooling	Existing (1977)**		Proposed (through 1987)	
	F*	N*	F	N
Mississippi:				
OT*	2902	50	500	0
WCT*	1770	1692	2750	1100
SC*	0	1600	0	0
Missouri:				
OT	2453	1311	2321	0
WCT	0	0	0	0

*F = Fossil; N = Nuclear; OT = Once-Through; WCT = Wet Cooling Tower; SC = Spray Canal

**includes plant retirements through 1982

could easily comply with the standards with closed-cycle cooling being the most economically feasible means. The existing standards now governing thermal discharges into the Mississippi River include a specified maximum allowable water temperature rise of 5°F over "natural" temperatures and a maximum allowable average temperature which varies from reach to reach (and month to month) along the entire length of the river. Natural temperature was not defined formally in the report and is defined for the present study as the temperature that would exist if no man-made heat inputs were imposed on the river. A summary of the existing thermal standards applicable to the Upper Mississippi River (Paily et al. 1976) is given in tables 2 and 3. Locations are identified by their distances in miles measured upstream along the channel from the intersection of the thalwegs of the Mississippi and Ohio Rivers.

Similar thermal standards exist for the Missouri River although, to the writers' knowledge, there has not been a collaborative effort between state and federal agencies to arrive at uniform standards, as in the case of the Mississippi River. A summary of the existing thermal standards applicable to the Missouri River (Paily et al. 1976) is given in table 4. Locations are measured upstream from the intersection of the thalwegs of the Missouri and Mississippi Rivers.

Thermal standards impact on both existing and proposed power plants in the following ways. For existing plants, stringent standards sometimes require operation of the plant at a derated output level to maintain river temperatures within the allowable limit. Thus, energy penalties and power production costs increase. If backfitting of the power plant with a closed-cycle cooling system is required to avoid this problem, the power plant will operate at less efficient energy conversion rates. For proposed power plants, similar comments can be made except outfitting economics (as opposed to backfitting economics) govern cooling-system selection. For once-through cooling systems, fuel consumption and cooling-related power-generation costs are heavily dependent upon the thermal standards, since the standards influence operation of the power plants and cooling-system by limiting the amount of heat discharged to the river.

TABLE 2

SUMMARY OF THERMAL STANDARDS FOR UPPER MISSISSIPPI RIVER

River Reach	State, and Controlling Agency	Allowable Temperature Rise Above Natural Conditions	Maximum Allowable Water Temperature
Reach 1: Lake Itasca to Lock and Dam No. 2, Hastings, Minn. (River Mile (RM) 815)	Minnesota State Pollution Control Agency	5°F	86°F, and/or as specified, for each month except 90°F max. from outlet of Metro Wastewater treat. Works to L & D No. 2
Reach 2: Lock and Dam No. 2, Hastings (RM 815) to Illinois border (RM 581)	Minnesota State Pollution Control Agency; and Wisconsin State Department of Natural Resources; and Iowa State Department of Environmental Quality	5°F	Specified for each month (table 3)
Reach 3: Wisconsin border (RM 581) to Missouri border (RM 361)	Iowa State Department of Environmental Quality; and Illinois State Pollution Control Board	5°F	3°F above the limits specified for each month (table 3)

TABLE 3

MAXIMUM ALLOWABLE WEEKLY AVERAGE WATER TEMPERATURES
(°F) IN UPPER MISSISSIPPI RIVER

Month	Reach 1*	Reach 2*	Reach 3*
January	40	40	45
February	40	40	45
March	48	54	57
April	60	65	68
May	72	75	78
June	78	84	85
July	83	84	86
August	83	84	86
September	78	82	85
October	68	73	75
November	50	58	65
December	40	48	52

* Reaches identified in Table 2

TABLE 4

SUMMARY OF THERMAL STANDARDS FOR MISSOURI RIVER

River Reach	State and Controlling Agency	Allowable Temperature Rise Above Natural Conditions	Maximum Allowable Water Temperature	Other
Upstream from RM 1600, inside Montana	Montana State Health and Environmental Sciences	1°F in range 32°-66°F; 0.5°F, above 66.5°F.	67°F, for natural temperature of 66.5 °F, or less.	Rate of decrease, 2°F/hour, up to 32°F.
Montana border (RM 1600) to South Dakota border (RM 1245)	North Dakota State Department of Health	5°F	85°F	
North Dakota border (RM 1245) to Big Bend Dam (RM 987)	South Dakota State Department of Environmental Protection	4°F	65°F	Maximum rate of increase, 2°F/hour.
Big Bend Dam (RM 987) to Nebraska border (RM 873)	South Dakota State Department of Environmental Protection	4°F	80°F	Maximum rate of increase, 2°F/hour.
South Dakota border (RM 873) to Sioux City, Iowa (RM 732)	Nebraska State Department of Environmental Control	4°F	80°F	Maximum rate of change 2°F/hour.

TABLE 4 (CONTINUED)

River Reach	State and Controlling Agency	Allowable Temperature Rise Above Natural Conditions	Maximum Allowable Water Temperature	Other
Sioux City, Iowa (RM 732) to Missouri border (RM 553)	Nebraska State Department of Environmental Control; and Iowa State Department of Environmental Quality	5°F	90°F	Maximum rate of change, 2°F/hour.
Iowa border (RM 553) to Kansas border (RM 490)	Nebraska State Department of Environmental Control; and Missouri State Clean Water Commission	5°F	90°F	

B. Modification of Thermal Standards. Studies of power plant cooling systems (Croley et al. 1976; Giaquinta et al. 1976) and investigations of the cooling potential of the Missouri and Mississippi Rivers (Paily et al. 1976; Su 1978; Giaquinta and Keng 1978) have revealed large water consumptions for cooling and large expenses borne by utilities in meeting river temperature standards at selected locations. These increases in water consumption and power-plant cooling costs are, of course, passed on to the consumer and are borne by society both directly and indirectly. With the importance of water, energy, and capital conservation, it becomes crucial that environmental thermal standards be considered carefully. It is now evident in many areas that existing river temperature standards may overprotect environmental concerns at the expense of added water losses and energy usage. There exists a need then for the adjustment of these standards to effect society's desired balance between environmental protection and cooling-related energy-production impacts.

There appear to be several logical modifications of standards that could be made for the Missouri and Upper Mississippi Rivers. There are also systematic changes that can be made in all state standards along the rivers. For example, the maximum allowable temperature rise can be increased or decreased. Furthermore, adoption of a uniform set of standards (in terms of maximum allowable temperature rises and maximum allowable temperatures during the annual cycle) for all northern states is plausible and can be made, on at least a hypothetical basis.

Existing power plants realize cooling system impacts that are dependent upon the standards regulating usage of the receiving waters. Depending upon the thermal standards, utilities might have to invest in ancillary cooling facilities and blowdown disposal facilities, face higher water consumption and operating costs of existing facilities, or both. In general, more stringent standards result in higher capital expenditures (for ancillary cooling systems and blowdown disposal facilities), higher water consumption, higher fuel costs (because of reduced efficiency at reduced cooling capacity), higher energy penalties, etc.

The U.S. Environmental Protection Agency has mandated that thermal discharges into natural rivers from power plants placed into service after

1 January 1970 (or 1974 depending on the size of the plant) will not be permitted after 1 July 1983 (Environmental Protection Agency 1974) unless it can be demonstrated conclusively that the discharge will not harm the aquatic biota. The standards were aimed at environmental enhancement with little consideration of the resultant costs to society. From parametric studies on thermal-standard modifications, an understanding of the water consumption and power generation consequences can be achieved. This information is essential for any reformulation of the thermal standards so that "trade-offs" between environmental and power-production objectives can be constructed. Such trade-offs form the most relevant basis for selection of standards as discussed below.

Since power-plant cooling impacts on a river are felt at downstream locations, the total impact of all plants on the river environment has been very difficult to assess for all meteorological conditions. Ideally, considerations of power generation and environmental preservation or enhancement change from point to point along a river. It has been impossible in the past to determine the best overall cooling strategy for all power plants on a major river in terms of a desired balance of power-production-related water consumption or economics and environmental acceptability. Such a determination would involve consideration of a very large number of complex and interacting factors not readily amenable to encapsulation with traditional optimization strategies. Instead, attention historically has been directed toward the creation of "standards" which attempt to "preserve" the environment to some extent and yet which allow "reasonable" use of the river waters for power plant cooling.

As evidenced by the widely varying state standards (see tables 2, 3, and 4), it is extremely difficult to determine a set of standards which adequately represents the environmental and beneficial use viewpoints. When standards are to be set, the question of interest becomes: What level of environmental preservation (or beneficial use) should be maintained with the standards? There have been many studies of the environmental ramifications of thermal loads on rivers. The common characteristics of them all is that the environmental impacts either are not quantifiable or are multidimensional,

or both. In any event, it has been impossible to associate a scalar numerical indication of environmental impact to a set of river standards. However, the environmental impact is real and must be addressed in any intelligent determination of river temperature standards. This problem of evaluating alternate standards in terms of their environmental impacts is typical of situations requiring subjective evaluations to be made.

There is an alternate method for considering environmental impacts. If the economic impact of environmental standards is understood by a decison maker (even if environmental impacts are not quantifiable and are multidimensional), then he or she can evaluate alternate sets of standards in terms of the "costs" required to meet those standards and the amount of environmental protection consequent to those constraints. (The "costs" include water and fuel consumption, energy penalties, power plant cooling expenses, etc.). In other words one can look at the trade-off costs of providing different levels of environmental protection (consequent to different sets of standards) to make a selection. One can then ask the question for each set of standards to be evaluated: "Are the environmental gains justified in relation to the expenditures?", or "Is it worth 'this' cost to achieve 'this' amount of environmental gain?" This question still involves a subjective choice, but it is much easier to answer than the original question: "How much environmental protection should be provided?" The question can be asked over and over for increasingly stringent sets of standards until a desired trade-off between environmental objectives and consequent water consumption and other costs is established.

The evaluation of water consumption trade-offs is currently possible by assessing the increases in power-related water consumption that are consequent to increasingly stringent sets of standards. Likewise, trade-offs in terms of energy (fuel) consumption, energy efficiency (conversion of natural resources), total cooling-related operating costs, etc., also can be constructed for increasingly stringent constraint sets to evaluate costs of environmental protection or enhancement.

C. Objectives and Scope of Study. The purpose of this study is to determine marginal (incremental) changes in total water consumption, fuel consumption, and power plant cooling expenses with changes in river temperature standards for the Missouri and Upper Mississippi Rivers in the MAPP geographical area. The estimation of cooling-related power-production costs is made for all power plants using water from both the Missouri and Mississippi Rivers upstream from the southern Nebraska and Iowa borders, respectively. A critical assessment of the value of thermal standards (that represent environmental protection and environmental enhancement objectives) in terms of actual water consumption and other costs is thereby enabled, so that subjective assessments can proceed with full knowledge of the trade-offs between environmental enhancement and the economic cost of power production.

The specific objectives are as follows:

A. Evaluate the marginal water consumption and power generation costs for several sets of river temperature standards along the Missouri and Upper Mississippi Rivers:
   1. consider only cooling-related power generation water consumption, costs, and penalties;
   2. consider all existing and future power plants which will use water from the two rivers; and
   3. assume "most likely" cooling system designs where none are currently specified.

B. Consider several river temperature constraint sets including:
   1. existing standards for all states bordering the rivers;
   2. several standards more relaxed than existing including the free-discharge or no-thermal-standard case;
   3. several standards stricter than existing including the case of no allowable thermal discharges.

C. Combine the results to estimate the following trade-offs between power production and environmental enhancement objectives through standards modification:
   1. marginal water-consumption trade-offs;
   2. marginal economic (cost) trade-offs.

II. BACKGROUND

A. Related Research. The evaluation of the trade-off costs of different thermal standards has not been thoroughly studied before. Neither specific site trade-offs nor comprehensive trade-offs for an entire river system have been analyzed. Of course, specific site trade-offs involving thermal standards have little meaning since environmental impacts are created by (and affect) all power plant cooling along the entire river, and standards cannot be set on a site-to-site basis (although variations are often allowed when downstream environmental impacts are demonstrated to be minimal).

Research efforts which supplied useful inputs to the present study include several projects at IIHR in the areas of thermal regimes of the Mississippi and Missouri Rivers (Paily et al. 1974, 1976; Paily and Kennedy 1974; Giaquinta and Keng 1978); optimization of dry-wet cooling towers (Cheng et al. 1976; Croley et al. 1976a, 1976b, 1976c); economics of back-fitting power plants with closed-cycle cooling systems (Giaquinta et al. 1976; Croley et al. 1978b), and a study of optimum mechanical-draft wet cooling towers to supplement once-through cooling at selected Missouri River sites (Croley et al. 1978a). The models which were developed and the data which were collected for these studies are very useful in the present project.

A recent report by Hu et al. (1978) gives results of a state-of-the-art study addressing consumptive water use and related costs of various steam-electric power plant cooling systems, the availability of water for all uses by area, and the impact of legal constraints on water use in the United States. The lack of data limited the study to consideration of only capital costs without assessment of annual operating costs.

The water consumption of nuclear power plants has been researched by the U.S. Geological Survey (Giusti and Meyer 1977). The amount of power generated, the name of the cooling water source, and the cooling method adopted for all nuclear power plants projected to be in operation by 1985 in the United States are tabulated, and the estimated annual evaporation at each power plant site is shown on a map of the conterminous United States.

B. Numerical Models. The computational scheme to assess the costs of thermal standards required the use of three models previously developed at the Iowa Institute of Hydraulic Research. The Iowa Thermal Regime Model (ITRM) examines the steady-state thermal regime along the study reaches of the Missouri and Upper Mississippi Rivers. A modified version of the model is used to locate regions where river temperatures exceed allowable limits for any prescribed set of thermal standards, and to assess river evaporation for heat loadings consequent with those thermal standards.

The model referred to as the Backfitting Model evaluates cooling-related costs of backfitting existing power plants (identified as requiring auxiliary cooling for a set of thermal standards by the ITRM) with mechanical draft wet cooling towers. The model referred to as the Outfitting Model computes cooling-related costs of outfitting proposed power plants (identified as requiring auxiliary cooling for a set of thermal standards by the ITRM) with once-through or closed-cycle (wet tower) cooling systems. Each of these three computer-based models is described in succeeding sections.

1. Iowa Thermal Regime Model (ITRM). The steady-state ITRM presented by Paily et al. (1976), is used to compute the thermal regimes. The model is based on a numerical solution of the one-dimensional convection-diffusion equation which predicts the longitudinal distribution of the cross-sectional average temperature along a river. The total river length is divided into smaller reaches, and temperature distributions are computed for each reach separately. The solutions for adjacent reaches are linked by the common conditions at the junction points connecting them. Each reach of the river can have multiple thermal inputs and tributary inflows. The formulation allows for changes in the channel characteristics, river flow rate, and weather data along the river.

The model is one-dimensional and assumes complete mixing of the heated effluent with the river. Therefore, exceedence of the maximum temperature rise thermal standard in this study is indicated by the fully mixed river temperature. This definition of thermal standard exceedence does not necessarily conform to state and federal regulations which sometimes specify mixing zone limitations.

To compute thermal discharges of proposed power plants, the model assumes values for in-plant efficiencies, overall plant efficiencies, and condenser temperature rises. Based on these assumptions, it is clear that the steady-state thermal regime model presents only an overview of the aggregate thermal profile of a river; it does not yield a detailed assessment of the actual temperature distribution. However, this model does give adequate representation of the spatial river temperature distribution as verification studies by Paily et al. (1976) have shown.

The ITRM was used to determine the temperature profile along the Mississippi and Missouri Rivers in the MAPP geographical area corresponding to average flow and weather conditions. The 7-day, 10-year low flow with average weather conditions for the months of August and November also were studied as the extreme case. The input data used for the computations are the following:

1. Heat loads from power plants of rated capacity 25 MW or greater, located on the main stem of the rivers;
2. monthly mean values of daily flow rates measured at U.S. Geological Survey gaging stations along the river;
3. monthly mean values of daily weather conditions including air temperature, wind speed, relative humidity, atmospheric pressure, cloud cover, and solar radiation measured at weather stations of the National Weather Service; and
4. channel top widths at various locations determined from river-channel cross sections reported by the U.S. Army Corps of Engineers. The river discharge, climatological variables, and channel geometry parameters were assumed to vary linearly between adjacent measuring stations.

A modified version of the thermal regime model was used to compute the heat assimilation capacity at various locations along the river corresponding to both the average and the 7-day, 10-year low flow conditions. The 7-day, 10-year low flow is the 7-day minimum average discharge occurring with a mean recurrence interval of 10 years. The 7-day, 10-year low flow is usually taken as the "worst case" criterion in accordance with federal and state

thermal regulations in outfitting proposed power plants and backfitting existing power plants with closed-cycle cooling systems. Another modification of the ITRM was used to calculate river evaporation rates along the river. The evaporation rate computed by determining the heat flux from the water due to evaporation is given by

$$\phi_E = \rho L(NV_a)\ (e_s - e_a) \tag{1}$$

For summer conditions,

$$NV_a = 1.107 \times 10^{-2} V_a + 9.34 \times 10^{-3}(\Delta\theta_v)^{1/3} \quad (\Delta\theta_v > \beta_v) \tag{2}$$

$$= 1.360 \times 10^{-2} V_a, \quad (\Delta\theta_v \leq \beta_v) \tag{3}$$

where

$$\Delta\theta_v = \{T_w(1 + 0.378e_s/P_a) - T_a(1 + 0.378e_a/P_a)\} \tag{4}$$

$$\beta_v = \{(1.36 - 1.107)V_a/9.34 \times 10^{-1}\}^3 \tag{5}$$

and for winter conditions,

$$NV_a = 2.09 \times 10^{-2} + 9.107 \times 10^{-4}(T_w - T_a) + 1.018 \times 10^{-2} V_a \tag{6}$$

In the above, ρ is the density of water (1 gm per cu cm); L is the latent heat of vaporization (597 cal per gm); T_w is the water temperature in °K; T_a is air temperature in °K; e_s is the saturation vapor pressure, in mb, corresponding to the dewpoint or relative humidity; V_a is the wind velocity, in m per sec; and P_a is the atmospheric pressure, in mb. The units of the variables in the above empirical relations were selected to yield the evaporation rate, ϕ_E/L, in units of gm per sq cm per day. Both $\Delta\theta_v$ and β_v

are defined as virtual temperature differences, with β_v being that virtual temperature difference at which the natural and heated evaporation are equal.

Equation 1 was presented by Ryan and Harleman (1973). The terms in equation 2 represent losses due to forced convection and free convection, respectively. Comparisons with lake-evaporation data were made in the paper with other formulas for field evaporation from a heated water surface. The MIT equation gave excellent results when compared with measured evaporative heat loss.

Evaporation rates corresponding to average flow conditions are computed for the following two cases: 1) no man-made heat sources are assumed to discharge into the river, which yields "natural" evaporation rates; and 2) thermal effluents are from existing and proposed power plants. Net evaporation rates due to the presence of the heat loads are then computed by subtracting the natural from the heated evaporation rate. The model does not include sublimation from ice and assumes zero evaporation when water temperatures drop below freezing.

2. Outfitting and Backfitting Models. The economics of power plant cooling performance is dependent mainly on the turbine-condenser subsystem characteristics and on the size and type of cooling system. Two basic types of turbines are considered in outfitting and backfitting as representative of those currently in use. The characteristics of these turbines and their nameplate capacities have been taken from Giaquinta et al. (1976). Turbine A is a high back-end loaded unit of contemporary design, while turbine B is a low back-end loaded unit representing some of the older plants. Heat-rate characteristics of turbines A and B are given by Giaquinta et al. (1976). Reference conditions for turbines A and B are listed in table 5.

Cooling characteristics curves may be determined for any specified size and type of cooling system by using the appropriate model. The cooling-characteristics curve for a once-through cooling system is primarily determined by the design condenser flow rate, stream temperature, and the actual heat-

TABLE 5

REFERENCE CONDITIONS FOR TURBINES A AND B

Turbine	Nameplate Capacity MW	Reference Back Pressure inch Hg abs (cm Hg abs)	Reference Heat Rejection Rates 10^9 Btu/hr (10^9kJ/hr) η_p=0.302	
			Old Fossil	New Nuclear
A	312.5	1.00	2.545	3.010
		(2.54)	(2.686)	(3.176)
B	275	1.00	3.313	3.918
		(2.54)	(1.797)	(2.125)

assimilation capacity of the stream which is defined as the product of the allowable temperature rise and the river flow rate.

For a mechanical draft wet cooling tower, the cooling characteristics curve is dependent on the tower size and the prevailing meteorological conditions. The cooling curves may then be determined from the basic thermodynamic model described by Croley et al. (1976b). The condenser size and capacity loss are determined from the operation point corresponding to design meteorological and stream conditions, while annual fuel consumption, make-up water, energy loss, and other quantities are obtained from operation points corresponding to actual meteorological and hydrologic conditions (Giaquinta et al. 1976).

Power plant cooling costs are composed of capital costs which include the cost of tower structures, once-through cooling structures, condensers, pump and pipe systems, and replacement capacity; and operating costs which consist of the costs of fuel, make-up water, water treatment, maintenance, and replacement energy. These costs are determined by using appropriate unit costs listed in table 6 and cost relations described by Croley et al. (1978a). The unit costs (provided by MAPP) are expressed in terms of 1977 dollars and are valid only for the MAPP region. The manner in which the capital and operating costs are combined to obtain the total cost depends primarily upon the general economic situation of the utility and the age of the affected unit. The total annual cost is produced by adding the operating cost to the product of the capital cost and the "fixed charge rate". The fixed charge rate reflects the annual cost of raising the required capital and includes such factors as interest on debt, required return on the stockholders' equity, depreciation of the equipment, property and income tax rates, etc. The value of the fixed charge rate to be used is determined mainly by the remaining life of the plant or unit (Environmental Protection Agency 1974).

The major factors considered in the economic assessment of backfitting an existing unit are:

1. the cost of installing the cooling tower, including materials, labor, site acquisition, and preparation;
2. the plant downtime for system changeover;

TABLE 6

UNIT COSTS*

Description	Cost
Unit cost of wet towers (mechanical draft)	$21/TU
Unit condenser cost	$12/sq. ft of surface area
Unit replacement capacity cost	$400,000/MW
Unit land cost	$5,000/acre
Unit make-up water cost	$1.8/1000 gals
Unit waste-water treatment cost	$0.15/1000 gals
Unit fuel cost	
nuclear	$0.001/kW-hr
fossil	$0.004/kW-hr
Unit maintenance cost of wet towers (mechanical draft)	$300/yr/cell
Unit replacement energy cost	$0.02/kW-hr

*(assumed to be spatially uniform in the region of study)

3. the provision of additional generating capacity to replace the power consumed by the cooling system;
4. the operation and maintenance costs of the cooling system; and
5. the additional cost of power generation due to limitations imposed by the use of the closed-cycle system.

The first three of these quantities are capital costs and the last two are operating costs incurred over the remaining lifetime of the plant. Once these factors have been determined, the total cost may be computed by using the fixed-charge-rate method.

It is possible to design mechanical draft wet towers of any size, but realistically the lowest-cost tower would be built in practice. Therefore, a range of tower sizes must be investigated at each site to determine the optimum design. In this study a range of tower heights between 35 ft and 55 ft is considered. The tower length of each plant is fixed by the design condenser flow rate and the water flow rate loading of the tower which is assumed to be 12.5 gpm/ft^2(plan area). It also is assumed that the power plants operate at full capacity eight-tenths of the year yielding an average plant capacity factor of 80 percent.

The characteristics of the power plant required for backfitting calculations are the rated capacity of the unit, the type of plant (fossil or nuclear), the thermodynamics of the existing turbine and condenser systems, and the economic situation of the utility operating the unit. Additional simplifications and assumptions made in the development of the backfitting model are:

1. the plant or unit is considered to operate with a constant, relatively low turbine back pressure, and the corresponding heat rejection rate is known for an existing open-cycle cooling system;
2. the existing condensers are retained without modification; and
3. the same capacity factor is used both before and after backfitting.

With these assumptions, computation of capital and operating costs of backfitting with a mechanicl draft wet cooling tower may be achieved by using

calculation procedures outlined by Croley et al. (1978b). Of foremost importance in the backfitting calculations are the capacity loss, the energy loss, the excess fuel consumption (the difference between the fuel consumption with an open-cycle cooling system and the backfitted system). The model also may be used for the computation of water consumption by the cooling tower.

III. PROCEDURE

Changes in thermal standards would alter allowable heat-assimilation capacities of a river and, hence, the operation of once-through cooling systems of power plants located along the river would be affected. If thermal discharges from power plants cause thermal standards to be exceeded, these power plants must either be derated or backfit with a closed-cycle cooling system. Associated with these alternatives are high energy losses and capital expenditures resulting from cooling tower construction and associated changes in operating costs and water evaporation as a result of the closed-cycle operation. The flowchart shown in figure 1 outlines the computational procedures used to compute cooling-related costs of power production for thermal standards more restrictive than existing. Major steps in the flow chart are indexed to the clarifying remarks listed below:

1. Data on existing thermal standards along the Upper Mississippi and Missouri Rivers were obtained from publications of various state government agencies applicable to the MAPP region. The allowable temperature rise "above the natural" presented in these thermal standards is assumed to refer to the temperature excess above the natural thermal regime of the river. Herein, natural thermal regime refers to the temperature distribution that would exist along the river if all man-made heat sources were absent.
2. The study months chosen for this project are February, May, August, and November. These months are assumed to represent the four seasons of the year and hence characterize the meteorologic and hydrologic conditions that prevail over the whole year.
3. The thermal regime is calculated with existing and proposed heat loads. Existing and proposed heat loads refer to thermal discharges from existing and proposed power plants, respectively. Existing heat loads also include those from industrial and municipal sources other than power plants. Proposed power

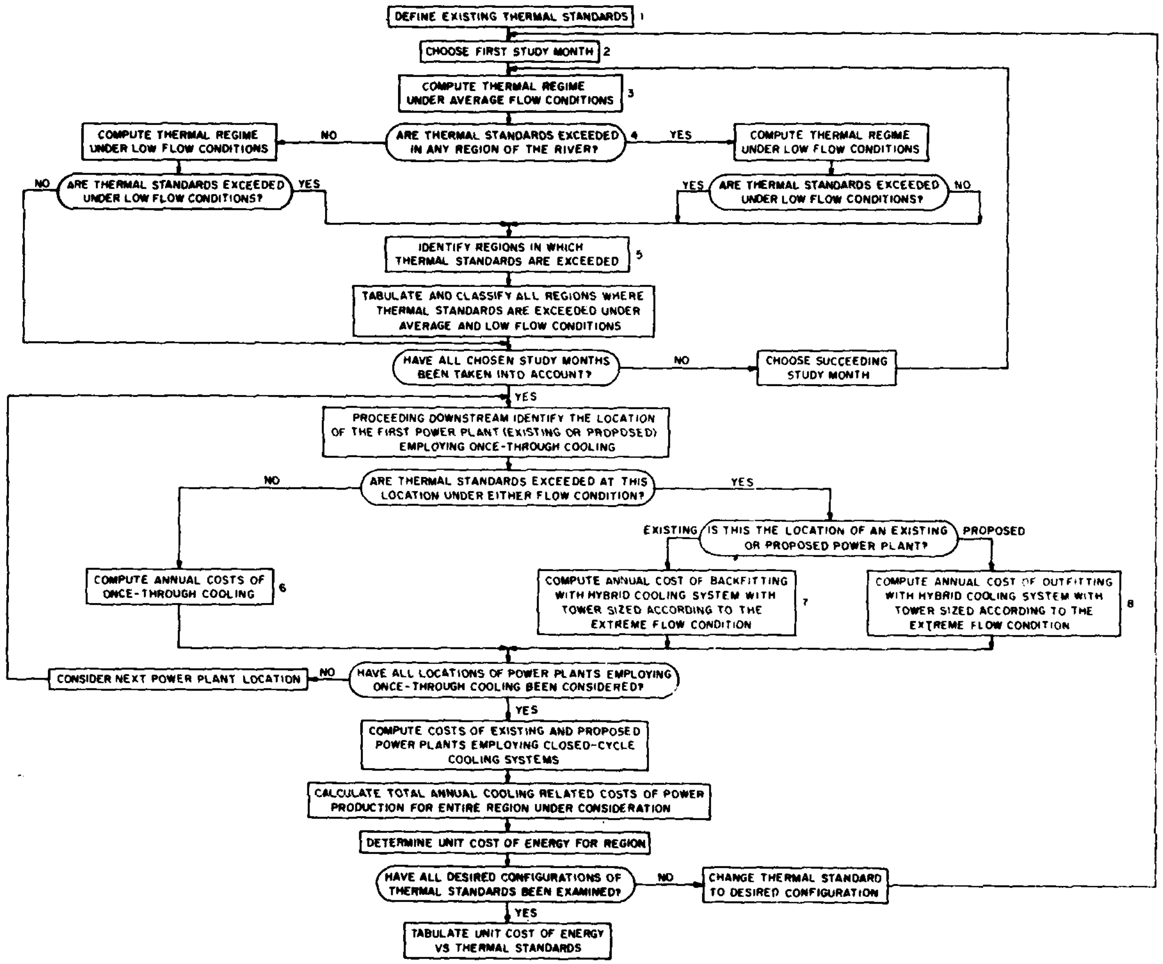

Figure 1. Computational flow chart

plants are those which the utilities have committed to construction as well as those future plants which have been sited. The location, size, and type of such power plants were obtained from information furnished by MAPP. The type of cooling system and condenser details of those plants are either known or chosen in accordance with the following assumptions:

a. proposed power plants would utilize once-through cooling unless otherwise specified.

b. proposed power plants with once-through cooling and unknown condenser details are assumed to operate with overall efficiencies of 36 percent and 32 percent, in-plant heat losses of 15 and 5 percent, and a condenser temperature rise of 18°F and 25°F for fossil and nuclear plants, respectively.

4. Cases in which thermal standards are exceeded are identified corresponding to the thermal regime computation using average flow conditions.

5. Regions where thermal standards are exceeded under low flow or average flow conditions are identified. Note: thermal standards exceedance under average flow conditions does not necessarily indicate that thermal standards are exceeded during low flow conditions. Because of the different rates of temperature decay for the two flow conditions, cumulative upstream effects on river temperature differ.

6. Capital and operating costs of once-through cooling systems are based on the assumption that the unit is operating at low turbine back pressures.

7. All hybrid cooling systems consist of once-through and mechanical draft wet cooling tower combinations. Hybrid systems are designed to meet thermal regulations under extreme flow (the worst hydrothermal case) conditions and are operated to provide the least cooling required to meet thermal regulations under average flow conditions. Capital and operating costs

of backfitting with hydbrid systems are computed based on an assumed linear variation of these costs between those incurred when backfitting with complete closed-cycle cooling and those for once-through cooling at the 80 percent capacity factor. Power plant costs at the 80 percent capacity factor are determined as follows: The power plant is first considered to operate at full throttle to determine the capital cost and annual operating cost. The full throttle annual operating cost is converted to an annual operating cost at the 80 percent capacity factor by multiplying relevant components of the full-throttle costs by 0.8 and adding the remaining cost components. Equivalent annual cost is then computed using the fixed-charge-rate method. All existing power plants are assumed to have a remaining life of 20 years.

8. The procedure used to compute the equivalent annual cost is the same as that outlined in clarifying remark 7, except that the costs considered here are outfitting costs. Proposed power plants are assumed to have an operating life of 35 years.

Costs of thermal standards more relaxed than the existing standards are computed in a manner different from that outlined in figure 1. The major benefit of relaxed thermal standards is additional power generation capacity at all locations along the river. In general, economies of scale would result in lower power generation cooling costs at larger power generation capacities.

This study considers sites of permissible power plants located along the Upper Mississippi and Missouri Rivers that were identified in the MAPP I study, (Paily et al. 1976). Permissible capacities at these locations at the existing and relaxed standards are determined.

IV. APPLICATIONS

A. The Upper Mississippi River System. The Mississippi River originates in the lake and forest country of north-central Minnesota near the village of Bemidji in the vicinity of Lake Itasca. The river follows a roughly circular course for the first 375 miles and then flows in a general southerly direction about 2100 miles to the Gulf of Mexico. The reach of the river extending about 1370 miles between its source and its junction with the Ohio River at Cairo, Illinois, is referred to as the Upper Mississippi River. A map of the river system and its major tributaries may be found in Paily et al. (1976). The Mid-Continent Area Power Pool geographic area contains the portions of the Upper Mississippi and Missouri Rivers lying upstream from the southern Iowa and Nebraska borders, as shown in figure 2 (Paily et al. 1976).

Monthly mean values of daily weather data for the 20-year period from 1953 to 1974 were determined from the data from seventeen first-order weather stations in the MAPP and adjacent areas. These weather stations are located along or close to the course of the Mississippi and Missouri Rivers, so that the data reported from them closely represent the climatic conditions along the two rivers. A map which depicts the locations of the weather stations is available elsewhere (Paily et al., (1976). A summary of the average values of the important meteorologic factors used in computation of the thermal regime is given in tables 7, 8, 9, and 10 corresponding to the months of February, May, August and November, respectively.

Monthly average values of daily flow rates at sixteen gaging stations along the Mississippi River were obtained from U.S. Geological Survey Water Supply publications. A summary of the mean daily flow rates and 7-day, 10-year low flow values at all the gaging stations used in the thermal regime calculations is given in table 11 and a map of the locations of the gaging stations is available elsewhere (Paily et al., 1967).

The temperature distributions and evaporation rates along the Mississippi River corresponding to average weather and flow conditions during the months of February, May, August and November were determined

Figure 2. Mississippi and Missouri Rivers and the MAPP geographical area

TABLE 7

SUMMARY OF MONTHLY MEAN VALUES OF DAILY
WEATHER CONDITIONS--FEBRUARY

Weather Station	Averaging Period	Air Temperature (°F)	Wind Speed (mph)	Relative Humidity (%)	Atmospheric Pressure (mb)	Cloud Cover (tenths)	Solar Radiation ($cal/cm^2/day$)
Glasgow, Mont.	1954-73	15.57	9.70	78.64	938.41	7.19	242.50
Williston, N.D.	1954-73	14.83	8.20	73.43	948.01	6.79	--
Huron, S.D.	1954-73	17.65	11.48	76.30	970.79	6.71	246.44
Aberdeen, S.D.	1965-73	14.50	11.76	72.78	971.04	6.53	--
Bismark, N.D.	1954-73	14.01	10.09	72.85	956.79	6.90	251.50
Sioux City, Ia.	1954-73	23.01	11.74	71.95	977.53	6.35	--
Omaha, Neb.	1954-73	26.96	11.28	70.00	980.70	6.11	281.77
St. Joseph, Mo.	1954-73	31.41	10.84	64.33	982.20	5.94	--
Kansas City, Mo.	1954-73	34.13	10.30	65.10	986.36	6.24	--
Columbia, Mo.	1954-73	33.10	--	70.16	989.04	6.36	263.39
St. Louis, Mo.	1954-73	34.88	10.63	69.25	998.14	6.52	--
Burlington, Ia.	1954-73	26.88	11.62	71.40	992.29	6.21	258.31
Moline, Ill.	1954-73	25.25	11.00	71.55	996.03	6.24	230.23
Dubuque, Ia.	1954-73	21.47	--	73.63	986.03	6.35	--
La Crosse, Wis.	1954-73	19.82	9.03	69.70	993.41	5.99	255.50
Minneapolis, Mn.	1954-73	16.92	10.57	69.90	985.39	6.07	--
St. Cloud, Mn.	1954-57						
Collegeville, Mn.	1933-41 1949-53	13.31	8.28	70.27	979.65	5.96	264.06

TABLE 8

SUMMARY OF MONTHLY MEAN VALUES OF DAILY WEATHER CONDITIONS--MAY

Weather Station	Averaging Period	Air Temperature (°F)	Wind Speed (mph)	Relative Humidity (%)	Atmospheric Pressure (mb)	Cloud Cover (tenths)	Solar Radiation ($cal/cm^2/day$)
Glasgow, Mont.	1954-73	54.83	11.50	55.08	937.66	6.66	518.65
Williston, N.D.	1954-73	54.57	9.99	55.73	946.66	6.47	--
Huron, S.D.	1954-73	57.09	12.72	65.55	966.67	6.29	518.61
Aberdeen, S.D.	1965-73	55.79	12.26	63.22	967.20	6.28	--
Bismark, N.D.	1954-73	54.63	12.19	59.55	952.46	6.56	540.50
Sioux City, Ia.	1954-73	61.69	12.71	61.20	973.29	6.21	--
Omaha, Neb.	1954-73	63.20	11.40	62.55	976.01	6.27	518.39
St. Joseph, Mo.	1954-73	65.42	11.03	58.60	979.34	5.97	--
Kansas City, Mo.	1954-73	66.49	10.26	62.05	982.82	6.19	--
Columbia, Mo.	1954-73	63.87	10.30	66.21	985.68	6.10	533.41
St. Louis,Mo.	1954-73	65.33	9.62	65.70	995.04	6.13	--
Burlington, Ia.	1954-73	61.94	10.74	65.58	989.98	6.12	468.36
Moline, Ill.	1954-73	61.09	10.62	65.30	992.85	6.15	491.83
Dubuque, Ia.	1954-73	58.12	--	62.13	982.48	6.45	--
La Crosse, Wis.	1954-73	58.93	10.06	63.90	989.74	6.37	506.86
Minneapolis, Mn.	1954-73	57.51	11.68	61.40	981.99	6.33	--
St. Cloud, Mn. Collegeville, Mn.	1954-57 1933-41 1949-53	55.31	9.06	62.40	975.99	6.47	479.77

TABLE 9

SUMMARY OF MONTHLY MEAN VALUES OF DAILY WEATHER CONDITIONS--AUGUST

Weather Station	Averaging Period	Air Temperature (°F)	Wind Speed (mph)	Relative Humidity (%)	Atmospheric Pressure (mb)	Cloud Cover (tenths)	Solar Radiation (cal/cm^2/day)
Glasgow, Mont.	1954-73	69.72	10.36	47.71	937.27	4.50	534.06
Williston, N.D.	1954-73	69.55	8.42	53.33	946.12	4.79	--
Huron, S.D.	1954-73	72.47	10.74	65.25	968.90	4.53	520.44
Aberdeen, S.D.	1965-73	70.86	9.99	60.78	967.60	4.23	--
Bismark, N.D.	1954-73	69.61	9.88	58.55	954.41	4.72	531.00
Sioux City, Ia.	1954-73	73.12	9.44	71.10	974.67	4.73	--
Omaha, Neb.	1954-73	75.16	8.83	70.00	977.54	4.66	523.29
St. Joseph, Mo.	1954-73	76.24	7.51	72.20	980.63	4.24	--
Kansas City, Mo.	1954-73	78.78	8.84	63.05	983.91	4.68	--
Columbia, Mo.	1954-73	76.67	8.16	67.90	986.98	4.97	522.67
St. Louis, Mo.	1954-73	77.03	7.60	68.90	995.96	5.25	--
Burlington, Ia.	1954-73	73.49	7.92	72.45	991.66	5.26	487.36
Moline, Ill.	1954-73	73.03	7.34	72.85	994.69	5.23	471.07
Dubuque, Ia.	1954-73	70.16	--	70.13	984.65	5.56	--
La Crosse, Wis.	1954-73	71.06	7.60	72.80	991.15	5.49	488.93
Minneapolis, Mn.	1954-73	69.86	9.05	68.75	983.54	5.22	--
St. Cloud, Mn.	1954-57						
Collegeville, Mn.	1933-41 1949-53	68.45	6.86	72.46	977.34	5.12	486.50

TABLE 10

SUMMARY OF MONTHLY MEAN VALUES OF DAILY WEATHER CONDITIONS--NOVEMBER

Weather Station	Averaging Period	Air Temperature (°F)	Wind Speed (mph)	Relative Humidity (%)	Atmospheric Pressure (mb)	Cloud Cover (tenths)	Solar Radiation (cal/cm^2/day)
Glasgow, Mont.	1954-73	29.23	10.30	72.53	938.64	7.19	150.69
Williston, N.D.	1954-73	28.14	8.66	74.14	947.19	7.23	--
Huron, S.D.	1954-73	32.30	11.98	70.80	969.35	6.70	211.78
Aberdeen, S.D.	1965-73	30.23	10.58	77.00	969.44	7.11	--
Bismark, N.D.	1954-73	28.53	10.32	68.05	955.79	7.12	157.88
Sioux City, Ia.	1954-73	36.82	11.70	69.40	978.44	6.42	--
Omaha, Neb.	1954-73	39.67	10.92	68.60	979.31	6.14	201.24
St. Joseph, Mo.	1954-73	42.67	10.07	69.17	982.92	5.72	--
Kansas City, Mo.	1954-73	43.36	9.59	64.40	985.39	5.83	--
Columbia, Mo.	1954-73	44.19	10.92	68.37	988.42	6.01	207.24
St. Louis, Mo.	1954-73	44.66	9.92	69.60	997.95	6.31	--
Burlington, Ia.	1954-73	39.95	10.92	72.75	992.14	6.48	182.42
Moline, Ill.	1954-73	39.20	10.15	71.80	995.25	6.89	153.33
Dubuque, Ia.	1954-73	36.10	--	70.63	985.67	7.16	--
La Crosse, Wis.	1954-73	35.34	10.19	75.10	991.66	7.21	149.57
Minneapolis, Mn.	1954-73	33.02	10.97	74.55	983.84	7.36	--
St. Cloud, Mn.	1954-57						
Collegeville, Mn.	1933-41 1949-53	30.45	8.90	73.86	977.68	7.43	143.47

TABLE 11

SUMMARY OF MONTHLY MEAN VALUES OF DAILY
FLOW RATES--MISSISSIPPI RIVER

Gaging Station	River Mile	Mean Daily Flow Rates in cfs					7-day, 10-yr Low Flow	
		Averaging Period	February	May	August	November	Period	Flow Rate (cfs)
Winnibigo-								
shish Dam	1248.0	1939-74	790	219	627	692	--	--
Grand Rapids	1182.0	1939-74	1714	1248	1204	1420	--	--
near Libby	1106.0	1949-74	1709	3799	1892	2059	1932-68	192
Aitkin	1056.0	1949-74	1809	5224	2399	2371	1946-68	476
Royalton	956.0	1939-74	2789	9952	4198	4095	1925-68	606
Anoka	864.8	1940-74	4130	15241	6707	6293	1933-68	951
St. Paul	839.3	1939-74	5107	22903	9035	8135	1907-68	1350
Prescott	811.4	1939-74	8003	32603	13801	13149	1930-68	3110
Winona	725.7	1939-74	14439	48499	20987	21546	1930-68	5570
McGregor	633.4	1939-74	17662	57467	25369	25665	1938-69	8604
Clinton	511.8	1939-74	27294	73032	34063	36501	1940-68	9800
Keokuk	364.2	1939-74	44412	105697	45294	48219	1941-73	10950

using the steady-state version of the Iowa Thermal Regime Model (ITRM) outlined in section II. River cross-section profiles and corresponding longitudinal water surface profiles furnished by the U.S. Army Corps of Engineers were used to obtain width-stage relationships for the river. The top widths were adjusted according to the flow rates, using stage-discharge relationships for the gaging stations. Cross section profiles were spaced 10 miles apart and intermediate top widths were calculated using linear interpolation between gaging stations and cross-section profiles. The details of the stage variations with discharge at each gaging station were obtained from the records of the U.S. Geological Survey.

There are 20 existing power plants, with a total of 48 units, in the MAPP area which utilize the Mississippi River water for once-through cooling. In addition, there are 2 proposed power plants, each with one unit, and 5 additional units at existing power plants for which the cooling system type has been specified. The locations of existing and proposed power plants are shown in figure 3. A summary of the characteristics of each plant is tabulated in table 12. Heat rejection rates to the Mississippi River of existing plants utilizing once-through/closed-cycle combination cooling are shown in table 13. Besides the power plants, industries and municipalities located along the river impose additional thermal loads on the river. The sources and quantities of the industrial and municipal discharges are given by Paily et al. (1976). The industrial and municipal effluents are small compared to those of power plants and generally are not large enough to produce any significant effect on the temperature profiles or evaporation rates so they are not included in the present study.

In order to identify the effects of power plant effluents on the natural conditions of a river, it is necessary to know its natural thermal regime. The natural thermal regime represents the temperature distributions that would exist if all man-made heat sources were absent. Since there were no available data representing the natural conditions of the Mississippi River, the natural thermal regime was calculated by the ITRM assuming that the upstream temperature (RM 1200) was at the equilibrium state.

Figure 3. Locations of existing and proposed thermal power plants along the Mississippi and Missouri Rivers in the MAPP area

TABLE 12

SUMMARY OF EXISTING AND PROPOSED POWER PLANTS IN THE MAPP REGION OF THE UPPER MISSISSIPPI RIVER

	PLANT			LOCATION	INSTALLATION			CONDENSER FLOW	
Utility	Name	Code *	City/County and State	River mile above Ohio River	Total Capacity (MWe)	Efficiency	No. of Units	Quantity (cfs)	Temp. Rise (°F)
MPL	Clay Boswell #1, 2	FOBE	Cohasset, Minn.	1187	150	.356	2	234	13.5
MPL	Clay Boswell #3	FWBE	Cohasset, Minn.	1187	350	.362	1	264	27.2
MPL	Clay Boswell #4	FWAP	Cohasset, Minn.	1187	500	.360	1	574	18.0
NSP	Sherburne County #1, 2	FWAE	Becker, Minn.	906	1420	.360	2	1631	18.0
NSP	Sherburne County #3, 4	FWAP	Becker, Minn.	906	1600	.360	2	1838	18.0
NSP	Monticello	NWBE	Monticello, Minn.	900	569	.307	1	645	28.0
UPA	Elk River #1,2,3	FOBE	Elk River, Minn.	891	50	.277	3	116	13.5

TABLE 12 (CONTINUED)

	PLANT		LOCATION		INSTALLATION			CONDENSER FLOW	
Utility	Name	Code *	City/County and State	River mile above Ohio River	Total Capacity (MWe)	Efficiency	No. of Units	Quantity (cfs)	Temp. Rise (°F)
NSP	Riverside #8	FOBE	Minneapolis, Minn.	852	239	.388	1	236	18.4
NSP	High Bridge #5,6	FOBE	St. Paul, Minn.	841	278	.370	2	303	18.0
NSP	Prairie Island #1,2	NWBE	Red Wing, Minn.	797	1123	.298	2	1360	27.4
DPC	Alma #1-5	FOBE	Alma, Wisc.	752	210	.325	5	286	18.0
DPC	Alma #6	FOAP	Alma, Wisc.	752	350	.339	1	446	18.0
DPC	Genoa #1A-2D,3	FOBE	Genoa, Wisc.	679	363	.387	2	380	17.3
DPC	Genoa #2	NOBE	Genoa, Wisc.	679	50	.249	1	143	15.0
ISP	Lansing #1-3	FOBE	Lansing Ia.	660	63	.281	3	138	13.9

TABLE 12 (CONTINUED)

	PLANT		LOCATION		INSTALLATION		CONDENSER FLOW		
Utility	Name	Code *	City/County and State	River mile above Ohio River	Total Capacity (MWe)	Efficiency	No. of Units	Quantity (cfs)	Temp. Rise (°F)
ISP	Lansing #4	FOAE	Lansing, Ia.	660	255	.322	1	318	20.0
DPC	Stoneman #1,2	FOBE	Cassville, Wisc.	607	52	.303	2	85	16.5
WPLC	Nelson Dewey	FOBE	Grant Co., Wisc.	605	227	.431	2	223	15.0
ISP	Dubuque #2-4	FOBE	Dubuque, Ia.	580	80	.247	1	185	16.0
IIGE ISP	Carroll County #1	NWAP	Savannah, Ill.	537	1100	.320	1	1316	25.0
ISP	M.L. Kapp #1,2	FOBE	Clinton, Ia.	518	239	.350	2	264	19.5
IIGE	Quad Cities #1,2	NSBE	Cordova, Ill.	502	1600	.302	2	2270	23.0
IIGE	Moline, #5,6,7	FOBE	Moline, Ill.	483	74	.270	3	161	14.9

TABLE 12 (CONTINUED)

	PLANT		LOCATION		INSTALLATION		CONDENSER FLOW		
Utility	Name	Code *	City/County and State	River mile above Ohio River	Total Capacity (MWe)	Efficiency	No. of Units	Quantity (cfs)	Temp. Rise (°F)
IIGE	Riverside #3,3HS,4,5	FOBE	Bettendorf, Ia.	482	224	.320	4	348	16.1
EILP	Fair #1,2	FOBE	Montpelier, Ia.	468	65	.251	2	113	20.7
IPS, IPL EILP	Louisa #1	FWAP	Muscatine, Ia.	457	650	.360	1	747	18.0
City of Muscatine	Muscatine #5-8	FOBE	Muscatine, Ia.	457	124	.336	3	191	15.0
City of Muscatine	Muscatine #9	FOAP	Muscatine, Ia.	457	150	.360	1	172	18.0
ISU	Burlington	FOBE	Burlington, Ia.	404	212	.381	1	180	22.0

*F = Fossil, N = Nuclear, O = Once-through cooling, W = Wet cooling tower, S = Spray canal, A = turbine A, B = turbine B, E = Existing plant, P = Proposed plant

TABLE 13

HEAT REJECTION RATES TO THE MISSISSIPPI RIVER

PLANT	HEAT REJECTION RATE (10^9 BTU/HR)			
	FEB.	MAY	AUG.	NOV.
Monticello	3.9	3.9	1.3	3.9
Prairie Island	1.8*	1.9	2.0	1.8*
Quad Cities		1.69*+		

* Heat discharge not related to plant load.
+ Computed based on annual average for 1977.

The various factors that influence the economics of backfitting depend to a large extent on the size and the performance of the closed-cycle cooling system being considered. The day-to-day performance of a system of given size, in turn, depends upon the meteorologic conditions at the site. Thus, the wet- and dry-bulb temperatures must be considered in the analysis of evaporative cooling towers. It is not possible to make a detailed evaluation of each site in the study region. However, table 14 gives the average wet- and dry-bulb temperatures at power plant locations along the Upper Mississippi River for the four study months, which, together with weather data in tables 7 through 10, is sufficient for purposes of this study.

In the design of closed-cycle cooling systems it is customary to use "design meteorologic conditions". Thus, for example, a "design wet-bulb temperature" is generally defined as the value which is not exceeded more than 5 percent of the time during the warmest four consecutive months, taken as June through September. Extreme wet- and dry-bulb temperatures which correspond to "extreme meteorologic conditions" also are used in the design of closed-cycle cooling systems. The extreme temperature is defined as 5°F plus the value which is not exceeded more than 1 percent of the time during the warmest four consecutive months. This definition is consistent with data from an earlier study in which extreme temperature was defined as

TABLE 14

MONTHLY AVERAGE WET AND DRY BULB TEMPERATURES (MISSISSIPPI R.)

Power Plant Location	WET BULB TEMP. °F				DRY BULB TEMP. °F			
	Feb.	May	Aug.	Nov.	Feb.	May	Aug.	Nov.
Cohasset, Minn.	6.1	46.2	60.2	24.4	7.6	53.0	66.5	26.5
Becker, Minn.	12.5	49.2	62.7	28.5	14.3	55.9	68.8	31.1
Monticello, Minn.	15.9	51.1	53.7	31.1	18.0	58.0	70.3	33.9
Elk River, Minn.	13.2	49.6	62.8	29.1	15.0	56.4	69.1	31.7
Minneapolis, Minn.	14.9	50.5	53.0	30.3	16.9	57.5	69.9	33.0
St. Paul, Minn.	15.0	50.5	63.0	30.4	17.0	57.6	69.9	33.1
Red Wing, Minn.	15.9	51.1	63.7	31.1	18.0	68.0	70.3	33.9
Alma, Wisc.	16.7	51.5	64.3	31.8	18.8	68.4	70.6	34.5
Genoa, Wisc.	17.9	52.0	64.8	32.6	20.1	58.8	70.9	35.5
Lansing, Ia.	18.2	51.9	64.6	32.6	20.4	58.7	70.8	35.6
Cassville, Wisc.	19.0	51.5	53.9	32.7	21.1	58.3	70.4	35.9
Grant Co., Wisc.	19.1	51.4	63.9	32.7	21.1	58.3	70.4	35.9
Dubuque, Ia.	19.5	51.1	63.6	32.7	21.5	58.1	70.2	36.1
Clinton, Ia.	21.7	53.3	65.7	34.7	24.0	60.1	72.0	38.1
Cordova, Ill.	22.2	53.8	66.3	35.2	24.6	60.6	72.5	38.7
Moline, Ill.	22.9	54.4	66.9	35.8	25.3	61.1	73.1	39.2
Montpelier, Ia.	23.5	54.6	66.9	35.9	25.6	61.3	73.1	39.4
Muscatine, Ia.	23.3	54.7	67.0	36.0	25.8	61.4	73.2	39.5
Burlington, Ia.	24.4	55.2	67.2	36.6	26.9	61.9	73.5	40.0

that value which is not exceeded more than 10 hours during the warmest four consecutive months (Giaquinta et al. 1976). Cooling tower manufacturers have available a list of design conditions appropriate for various sites in the United States (The Marley Company). Table 15 shows the design and extreme wet- and dry-bulb temperatures along the Upper Mississippi River. For locations between stations given in the reference, linear interpolation is used.

1. Water Consumption. Water Consumption resulting from power-plant operation is due to the increased river temperatures caused by heated effluents, and to evaporation from cooling towers. Natural evaporation (without power plants) from the study reach was obtained from the ITRM with the appropriate data set and is shown in figure 4. The annual equivalent of this figure integrated over the river is 266 million m^3. The variations in natural evaporation are a result, principally, of the natural variations of the top width of the river. To eliminate the effects of top width from this and succeeding evaporation figures, the unit natural evaporation is calculated by dividing evaporation by the river width and is depicted in figure 5. Now, the dips and peaks in the curve are seen to correspond to the locations of the weather stations which are labeled at the top of figure 5. This is due to the assumed linear variation of meteorologic data between weather stations. It is noted that natural evaporation for the month of February and November in Minnesota and Wisconsin is zero because of the presence of ice cover on the river during these months. As noted earlier, sublimation from ice is neglected in this study.

The unit river evaporation corresponding to the existing and proposed power plants with existing thermal standards was computed with the ITRM and appropriate data sets. The unit natural evaporation of figure 5 was subtracted from the evaporation when heat loads are present to give the unit net evaporation from the river, which is plotted for August conditions in figure 6. Unit net evaporation for August has a distribution similar to the months of May and November so those figures are not shown in this report. It is important to note that this figure pertains to unit net river evaporation only and does not include the cooling-related evaporation losses from wet

TABLE 15

DESIGN AND EXTREME WET AND DRY
BULB TEMPERATURES (MISSISSIPPI R.)

Location		DRY BULB TEMP. °F		WET BULB TEMP. °F	
City/County and State	River Mile above Ohio River	Design	Extreme	Design	Extreme
Cohasset, Minn.	1187	83.75	96.50	70.26	79.00
Becker, Minn.	906	85.64	95.24	73.40	81.52
Monticello, Minn.	900	85.68	96.79	73.46	81.57
Elk River, Minn.	891	84.42	95.95	71.36	79.89
Minneapolis, Minn.	852	85.97	96.94	74.00	82.00
Red Wing, Minn.	797	85.64	96.28	74.00	82.00
Alma, Wisc.	752	85.36	95.71	74.00	82.00
Genoa, Wisc.	679	84.84	94.68	73.84	81.84
Lansing, Iowa	660	84.68	94.68	73.68	81.68
Cassville, Wisc.	607	84.33	94.33	73.33	81.33
Grant Co., Wisc.	605	84.21	94.21	73.21	81.21
Dubuque, Iowa	580	84.00	94.00	73.00	81.00

TABLE 15 (CONTINUED)

Location		DRY BULB TEMP. °F		WET BULB TEMP. °F	
City/County and State	River Mile above Ohio River	Design	Extreme	Design	Extreme
Clinton, Iowa	518	86.64	96.64	74.32	82.32
Cordova, Iowa	502	87.32	97.32	74.66	82.66
Moline, Ill.	483	88.04	98.07	75.07	83.07
Montpelier, Iowa	468	88.22	98.44	75.44	83.44
Muscatine, Iowa	457	88.35	98.70	75.70	83.70
Burlington, Iowa	404	89.99	100.00	77.00	85.00

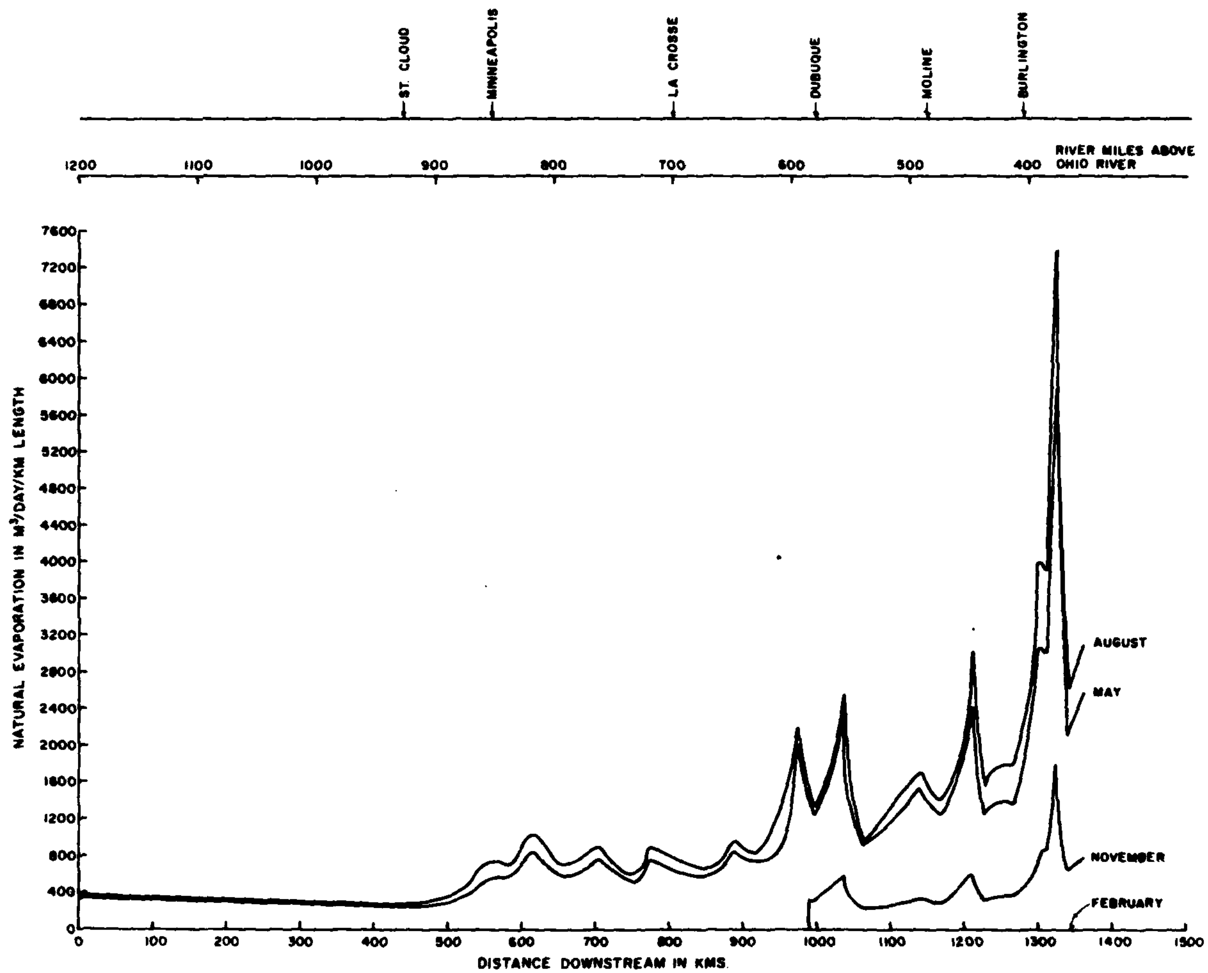

Figure 4. Natural evaporation along the Upper Mississippi River

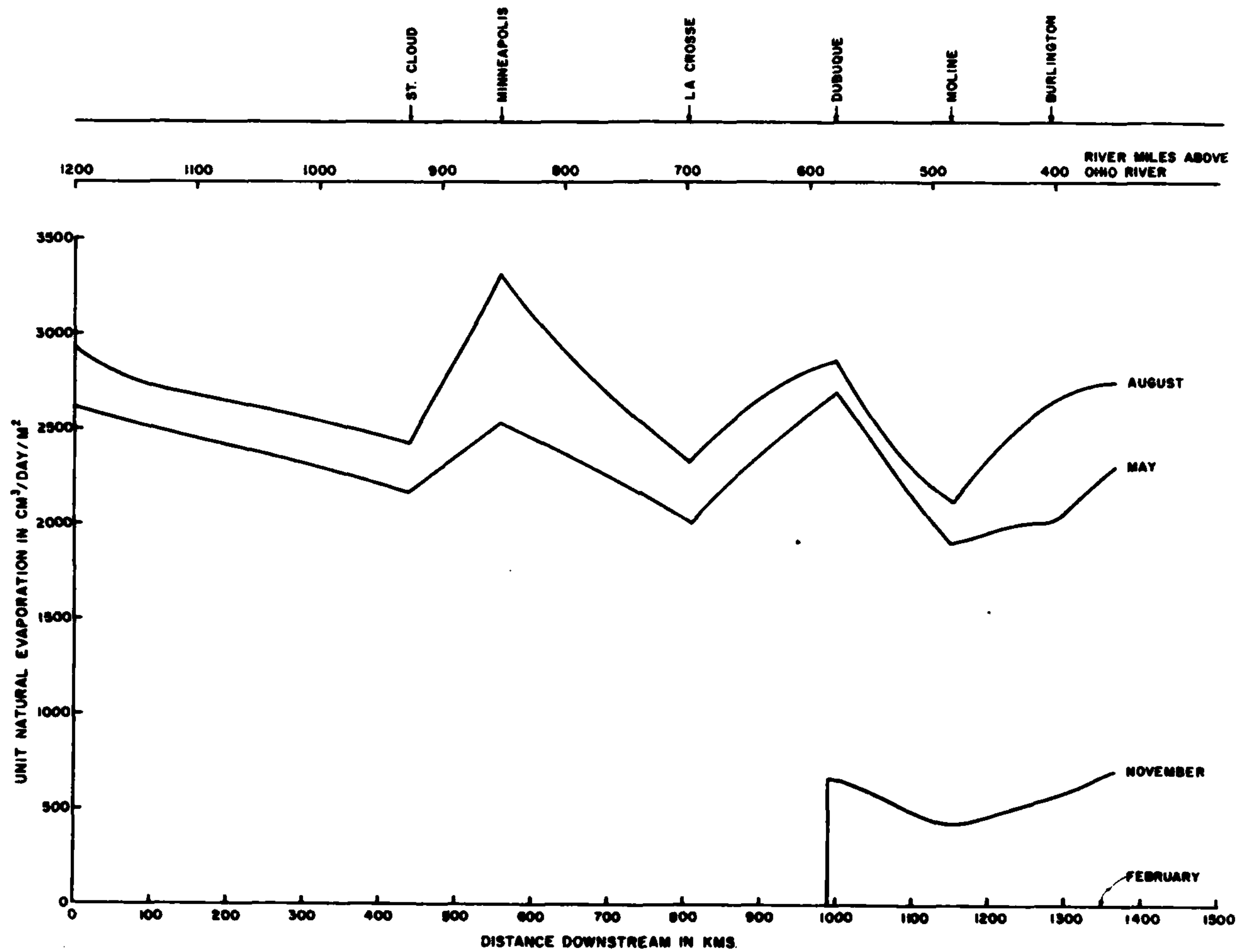

Figure 5. Unit natural evaporation along the Upper Mississippi River

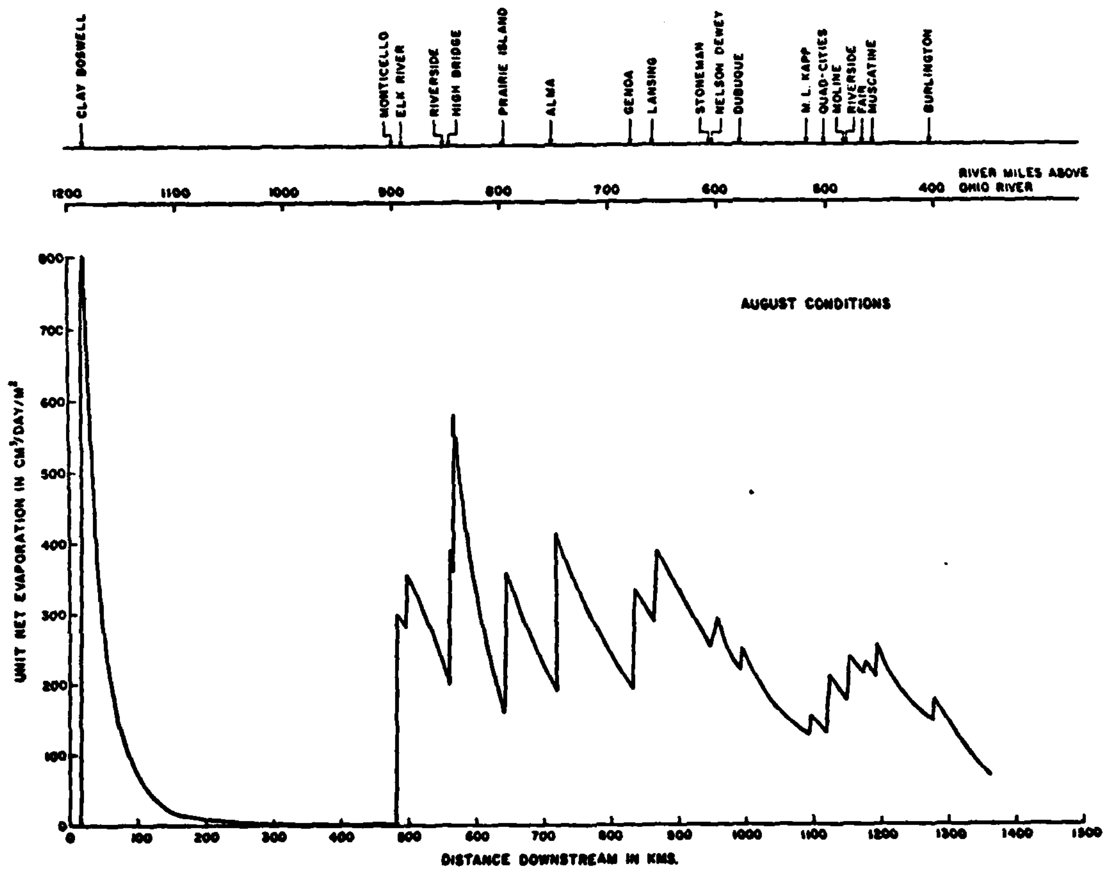

Figure 6. Unit net evaporation for August along the Upper Mississippi River

cooling towers since it is not possible to present these losses on a unit basis. Sharp spikes in the evaporation curve are a result of thermal discharges at those locations. Certain interesting features can be observed in the unit net evaporation for the month of February, figure 7. As a result of ice cover, no evaporation occurs unless the temperature of the river water is above 0°C as a consequence of heated discharges from power plants. Water temperatures above freezing are not sustained over a long reach of the river because of adverse meteorological conditions; therefore, the unit net evaporation abruptly drops to zero. It also should be noticed that the magnitude of the evaporation rates is much greater than the corresponding rates for August. This increase is primarily due to the existing heat loads which keep a large portion of the river free of ice cover resulting in additional heat input from the atmosphere in the form of solar and atmospheric radiation.

By integrating the net river evaporation along the river and over the year and adding the total evaporation from any wet cooling towers, the total annual evaporation can be calculated for each set of thermal standards. This calculation was made for the free-discharge condition, the existing and no-discharge thermal standards, and for three intermediate standards. The results are tabulated in table 16. Note that the intermediate thermal standards are defined by their respective decrements from the existing allowable temperature rise of 5°F; the 2°F decrement thermal standard therefore refers to an allowable temperature rise of 3°F. It is seen from this table that the existing standards result in an annual water consumption increase of about 23 million m^3 over the free-discharge condition of 106 million m^3 (an increase of 22 percent). The no-discharge standard represents an annual increase of 42 million m^3 over the free-discharge condition (an increase of 40 percent) and an annual increase of 19 million m^3 over the existing thermal standard of 129 million m^3 (an increase of 15 percent). Water consumption for the 2°F, 3°F and the 4°F decrement standards is not significantly larger than that for the existing standard since there is no substantial increase in the number of plants requiring backfitting with wet towers at these standards.

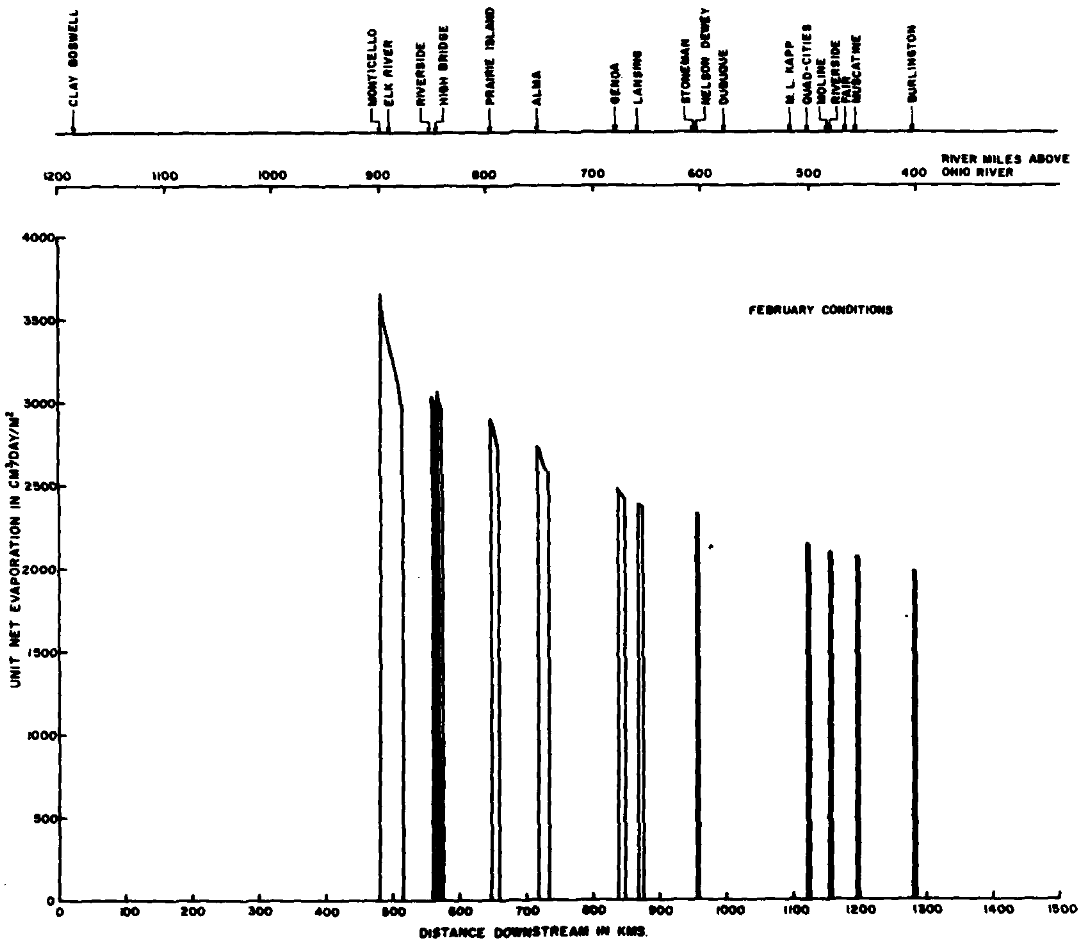

Figure 7. Unit net evaporation for February along the Upper Mississippi River

TABLE 16

WATER CONSUMPTION OF DIFFERENT THERMAL STANDARDS
(MISSISSIPPI R.)

Thermal Standard	Net Annual Evaporation from River Surface, $10^6 m^3$	Annual Water Consumption of Wet Towers $10^6 m^3$	Total Annual Evaporation $10^6 m^3$
Free Discharge	105.6	0	105.6
Existing	37.29	91.48	128.8
2°F decrement	37.05	91.92	129.0
3°F decrement	36.31	93.20	129.5
4°F decrement	31.81	97.98	129.8
No Discharge	0	148.1	148.1

Net annual evaporation from the river water surface listed in table 16 for various thermal standards is obtained by summing net evaporation along the reach shown in figures 6 and 7 and downstream until the effects of power plant discharges become negligible. The net annual evaporation from the river surface is therefore the total annual consumptive use of water resulting from the operation of power plants employing once-through cooling. The total natural evaporation computation is only along the study reach. Care should be taken when comparing the net annual evaporation shown in table 16 with the total annual natural evaporation of 266 million m^3.

Net evaporation from the river surface represents total evaporation for the free-discharge condition (no cooling tower evaporation). At the existing standards, a number of plants utilize closed-cycle cooling systems; hence, net evaporation from the river surface is less though evaporation from wet towers and total water consumption are higher. Total water consumption increases as thermal standards become more restrictive and is the highest for the no-discharge thermal standard because, for comparable cooling duties, water consumption from wet towers is larger than evaporation from the river surface.

2. Economic costs. Costs incurred when a power plant uses the once-through cooling mode were computed for all power plants along the

Mississippi River. As defined earlier, the term "costs" refers to cooling-related costs which are expressed in 1977 dollars. The free-discharge thermal standard allows all power plants to use once-through cooling. It is assumed that all power plants utilizing once-through cooling will operate at low turbine back pressures. The energy losses associated with higher turbine back pressures as a result of high river temperatures are not significant and hence are ignored in the computation of once-through cooling costs.

The computed costs of the free-discharge thermal standard are listed in table 17. The average cooling-related cost of power production at the free-discharge thermal standard is 8.711 mills kW/hr. The large operating costs of fossil-fueled power plants as compared with nuclear plants are primarily due to the unit cost of fossil fuel which is four times greater than the unit cost of nuclear fuel. The total annual costs listed in the last two columns of table 17 are cooling-related costs described previously in section II. The total annual cost in units of mills/kW-hr is a weighted average that accounts for power generation capacity.

Costs for the existing and no-discharge thermal standards are computed from the backfitting and outfitting models for each utility identified by the ITRM as requiring auxiliary cooling. Costs for existing thermal standards are presented in table 18. These computed results indicate that the average cooling-related cost of electrical energy generation in the region of study is of the order of 10.49 mills/kW-hr for the present thermal standards, which represents a relative increase of about 1.78 mills/kW-hr over the free-discharge case (an increase of 20.4 percent). The value of 1.78 mills/kW-hr may then be considered as the average "cost" of the existing thermal standards.

The no-discharge thermal standard involves additional costs incurred as a result of backfitting once-through cooling systems with cooling towers; the costs are listed in table 19. It is seen that the no-discharge thermal standard represents an average increase of 1.09 mills/kW-hr over the existing average annual cost (an increase of 10.4 percent). The "cost" of the no-discharge standard is, therefore, of the order of 2.87 mills/kW-hr as compared

TABLE 17

COMPUTED COSTS OF FREE-DISCHARGE THERMAL STANDARD (MISSISSIPPI R.)

Plant & Unit No.	Location (RM)	Capacity (MW)	Code*	Capital Cost (millions of dollars)	Annual Operating Costs (millions of dollars)	Total Annual Cost (millions of dollars)	Costs (mills/ kW-hr)
Clay Boswell #1,2	1187	150	FOBE	2.187	11.80	12.13	11.54
Clay Boswell #3	1187	350	FWBE	4.134	27.26	27.87	11.36
Clay Boswell #4	1187	500	FWAP	5.906	38.93	39.81	11.36
Sherburne County #1,2	906	1420	FWAE	16.76	110.5	113.0	11.36
Sherburne County #3,4	906	1600	FWAP	18.89	124.5	127.3	11.36
Monticello	900	569	NWBE	7.624	12.96	14.08	3.530
Elk River #1,2,3	891	50	FOBE	1.089	5.055	5.216	14.88
Riverside #8	852	239	FOBE	2.443	17.32	17.68	10.56
High Bridge #5,6	841	278	FOBE	3.121	21.00	21.47	11.02
Prairie Island #1,2	797	1123	NWBE	15.97	26.38	28.74	3.652
Alma #1-5	753	210	FOBE	2.943	18.11	18.55	12.60
Alma #6	753	350	FOAP	4.585	29.00	29.68	12.10
Genoa #1A-2D,3	679	363	FOBE	3.868	26.28	26.86	10.56
Genoa #2	679	50	NOBE	1.380	1.408	1.612	4.600
Lansing #1,2,3	660	63	FOBE	1.311	6.273	6.466	14.65
Lansing #4	660	255	FOAE	3.382	22.21	22.71	12.71
Stoneman #1,2	607	52	FOBE	0.858	4.796	4.923	13.51
Nelson Dewey	605	227	FOBE	2.160	14.75	15.07	9.472
Dubuque #2-4	580	80	FOBE	1.834	9.088	9.359	16.69
Carroll County #1	537	1100	NWAP	15.02	24.09	26.31	3.413
M.L. Kapp #1,2	518	239	FOBE	2.778	19.07	19.48	11.66
Quad Cities #1,2	502	1600	NSBE	25.24	37.16	40.89	3.650
Moline #5,6,7	483	74	FOBE	1.560	7.656	7.886	15.21
Riverside #3,3HS,4,5	482	224	FOBE	3.455	19.59	20.10	12.81

TABLE 17 (CONTINUED)

Plant & Unit No.	Location (RM)	Capacity (MW)	Code*	Capital Cost (millions of dollars)	Annual Operating Costs (millions of dollars)	Total Annual Cost (millions of dollars)	Costs (mills/ kW-hr)
Fair #1,2	468	65	FOBE	1.220	7.253	7.433	16.31
Louisa #1	457	650	FWAP	7.677	50.61	51.75	11.36
Muscatine #5-8	457	124	FOBE	1.852	10.30	10.58	12.17
Muscatine #9	457	150	FOAP	1.770	11.66	11.93	11.34
Burlington	404	212	FOBE	1.973	15.58	15.87	10.68
TOTAL		12,364				754.8	8.711

* F = Fossil, N = Nuclear, O = Once-through, W = Wet cooling tower, S = Spray Canal, A = turbine A, B = turbine B, E = Existing plant, P = Proposed plant

TABLE 18

COMPUTED COSTS OF EXISTING THERMAL STANDARDS (MISSISSIPPI R.)

Plant & Unit No.	Location (RM)	Capacity (MW)	Code*	Capital Cost (millions of dollars)	Annual Operating Costs (millions of dollars)	Total Annual Cost (millions of dollars)	Costs (mills/kW-hr)
Clay Boswell #1-2	1187	150	FOBE	8.950	11.81	13.01	12.38
Clay Boswell #3	1187	350	FWBE	22.96	30.45	33.84	13.80
Clay Boswell #4	1187	500	FWAP	13.20	42.73	44.68	12.75
Sherburne County #1,2	906	1420	FWAE	35.99	121.6	126.9	12.75
Sherburne County #3,4	906	1600	FWAP	40.30	137.0	142.9	12.75
Monticello	900	569	NWBE	111.8	15.41	31.90	8.000
Elk River #1,2,3	891	50	FOBE	5.860	5.055	6.069	17.32
Riverside #8	852	239	FOBE	2.443	17.32	17.68	10.56
High Bridge #5,6	841	278	FOBE	3.121	21.01	21.47	11.02
Prairie Island #1,2	797	1123	NWBE	49.80	36.93	44.27	5.626
Alma #1-5	753	210	FOBE	2.943	18.11	18.55	12.60
Alma #6	753	350	FOAP	4.585	29.00	29.68	12.10
Genoa #1A-2D,3	679	363	FOBE	3.868	26.29	26.86	10.56
Genoa #2	679	50	NOBE	1.380	1.408	1.612	4.600
Lansing #1,2,3	660	63	FOBE	1.311	6.273	6.466	14.65
Lansing #4	660	255	FOAE	3.382	22.22	22.71	12.71
Stoneman #1,2	607	52	FOBE	.858	4.796	4.923	13.51
Nelson Dewey	605	227	FOBE	2.160	14.75	15.07	9.472
Dubuque #2-4	580	80	FOBE	1.834	9.088	9.359	16.69
Carroll County #1	537	1100	NWAP	39.05	36.84	42.60	5.526
M.L. Kapp #1,2	518	239	FOBE	2.778	19.07	19.48	11.66
Quad Cities #1,2	502	1600	NSBE	240.5	62.40	97.87	8.729
Moline #5,6,7	483	74	FOBE	1.560	7.656	7.886	15.21
Riverside #3,3HS,4,5	482	224	FOBE	3.455	19.59	20.10	12.81

TABLE 18 (CONTINUED)

Plant & Unit No.	Location (RM)	Capacity (MW)	Code*	Capital Cost (millions of dollars)	Annual Operating Costs (millions of dollars)	Total Annual Cost (millions of dollars)	Costs (mills/kW-hr)
Fair #1,2	468	65	FOBE	1.220	7.253	7.433	16.31
Louisa #1	457	650	FWAP	17.40	55.91	57.03	12.52
Muscatine #5-8	457	124	FOBE	1.852	10.30	10.58	12.17
Muscatine #9	457	150	FOAP	1.770	11.66	11.93	11.34
Burlington	404	212	FOBE	1.973	15.58	15.87	10.68
TOTAL						908.7	10.49

* F = Fossil, N = Nuclear, O = Once-through, W = Wet cooling tower, S = Spray canal, A = turbine A, B = turbine B, E = Existing plant, P = Proposed plant

TABLE 19

COMPUTED COSTS OF NO-DISCHARGE THERMAL STANDARD (MISSISSIPPI R.)

Plant & Unit No.	Location (RM)	Capacity (MW)	Code*	Capital Cost (millions of dollars)	Annual Operating Costs (millions of dollars)	Total Annual Cost (millions of dollars)	Costs (mills/kW-hr)
Clay Boswell #1,2	1187	150	FOBE	11.90	13.10	15.16	14.42
Clay Boswell #3	1187	350	FWBE	22.96	30.45	33.84	13.80
Clay Boswell #4	1187	500	FWAP	13.20	42.74	44.69	12.72
Sherburne County #1,2	906	1420	FWAE	35.99	121.6	126.9	12.75
Sherburne County #3,4	906	1600	FWAP	40.30	137.0	142.9	12.75
Monticello	900	569	NWBE	111.8	25.24	41.73	10.47
Elk River #1,2,3	891	50	FOBE	5.855	5.752	6.766	19.31
Riverside #8	852	239	FOBE	17.49	19.35	22.40	13.38
High Bridge #5,6	841	278	FOBE	20.65	23.62	27.22	13.97
Prairie Island #1,2	797	1123	NWBE	49.80	40.47	47.82	6.076
Alma #1-5	753	210	FOBE	20.24	20.56	24.09	16.37
Alma #6	753	350	FOAP	14.39	32.13	34.25	13.97
Genoa #1A-2D,3	679	363	FOBE	25.44	29.49	33.92	13.34
Genoa #2	679	50	NOBE	8.804	2.422	3.768	10.75
Lansing #1,2,3	660	63	FOBE	7.354	7.167	8.442	19.12
Lansing #4	660	255	FOAE	10.83	24.67	26.50	14.83
Stoneman #1,2	607	52	FOBE	5.359	5.510	6.442	17.68
Nelson Dewey	605	227	FOBE	13.22	16.33	18.63	11.71
Dubuque #2-4	580	80	FOBE	11.72	10.49	12.53	22.35
Carroll County #1	537	1100	NWAP	39.05	36.83	42.59	5.525
M.L. Kapp #1,2	518	239	FOBE	20.55	21.73	25.32	15.12
Quad Cities #1,2	502	1600	NSBE	240.5	67.96	103.4	9.225
Moline #5,6,7	483	74	FOBE	9.229	8.854	10.46	20.16
Riverside #3,3HS,4,5	482	224	FOBE	21.49	22.50	26.24	16.71

TABLE 19 (CONTINUED)

Plant & Unit No.	Location (RM)	Capacity (MW)	Code*	Capital Cost (millions of dollars)	Annual Operating Costs (millions of dollars)	Total Annual Cost (millions of dollars)	Costs (mills/ kW-hr)
Fair #1,2	468	65	FOBE	9.373	8.559	10.20	22.39
Louisa #1	457	650	FWAP	17.40	55.90	57.03	12.52
Muscatine #5-8	457	124	FOBE	11.32	11.74	13.71	15.78
Muscatine #9	457	150	FOAP	4.997	12.89	13.63	12.96
Burlington	404	212	FOBE	25.71	17.89	22.43	15.10
TOTAL		12,364				1003.	11.58

* F = Fossil, N = Nuclear, O = Once-through, W = Wet cooling tower, S = Spray canal, A = turbine A, B = turbine B, E = Existing plant, P = Proposed plant

TABLE 20

REGIONAL COST COMPARISONS OF DIFFERENT THERMAL STANDARDS (MISSISSIPPI R.)

Thermal Standard	Total Costs		Incremental "cost" of standard above free-discharge	
	Annual 10^6 dollars	mills/ kW-hr	Annual 10^6 dollars	mills/ kW-hr
Free Discharge	754.8	8.711		
Existing	908.7	10.49	153.9	1.779
2°F Decrement	912.6	10.53	157.8	1.819
3°F Decrement	918.8	10.60	164.0	1.889
4°F Decrement	939.3	10.84	184.5	2.129
No Discharge	1003.	11.58	248.2	2.869

to the free-discharge condition (an increase of 32.9 percent). Similar procedures are adopted to compute the cost of the 2°F, 3°F, and 4°F decrement thermal standards. All regional cost figures are summarized in table 20.

The fuel-consumption cost with a once-through cooling system operating in a free-discharge mode turns out to be the same as or higher than the corresponding cost for the same power plant outfitted with a mechanical draft wet cooling tower. This phenomenon also is observed in the backfitting operation and is due to the derating of some plants with wet towers at certain times, because of adverse meteorologic conditions. Consequently, fuel consumption is lower with the wet tower. Under these conditions, however, large amounts of replacement energy are required with high replacement energy costs. The decrease in fuel consumption of plants with cooling towers is, of course, counteracted by an increased fuel consumption of the plants supplying the replacement energy.

The existing thermal standard produces additional costs in terms of energy losses. These energy losses occur because the power plant outfitted with a wet tower operates at a higher turbine back pressure and must supply the required energy to run the fans and pumps of the cooling tower. The amount of annual energy loss that occurs at the existing thermal standard is 1,133 million kW-hr or 129 MW. The total annual energy loss which would occur at the no-discharge thermal standard is 2,140 million kW-hr or 244 MW.

These energy losses represent the amount of energy that must be purchased from other utilities.

For the Mississippi River, the only exceedances of existing thermal standards occur during low flow conditions at the Clay Boswell and Elk River power plants. The costs of existing thermal standards at these plants therefore include capital costs of wet towers designed to provide sufficient cooling capacity at the 7-day, 10-year low flow.

Cost computations have been made for the free-discharge, existing, and no-discharge thermal standards, and for other intermediate standards more restrictive than existing. To address hypothetical standards more relaxed than existing (the free-discharge standard is considered merely as a base to compute the "incremental" costs), two other standards are examined which are the 2°F and 4°F increment thermal standards representing a 2°F and 4°F increase over the existing allowable temperature rise, respectively. On the Mississippi River, the former standard would refer to an allowable temperature rise of 7°F and the latter to a 9°F allowable temperature rise.

Throughout this study it has been assumed that existing and proposed power plants would utilize specified types of cooling systems unless they are required to backfit with wet towers as a result of thermal standard exceedances. Since no exceedances occur at the existing standards under average flow conditions and few occur at the low-flow conditions, no significant changes in costs may be expected at standards more relaxed than existing. It is evident however, that there would be considerably more assimilation capacity in the river at the relaxed standards.

The real benefit of relaxed standards is, therefore, the ability to size larger future "permissible" plants at specified locations. However, for once-through cooling there is no substantial savings in cost in mills/kW-hr as a result of greater installed capacity.

Locations of permissible plants under investigation along the Mississippi River are the same as those identified previously by Paily et al. (1976). Permissible plant capacities (assuming 100 percent capacity factor) at these locations for the existing and the 2°F and 4°F increment thermal standards under average flow conditions are obtained through the sequential

use of the ITRM. Existing and proposed power plants are assumed to operate at the 80 percent capacity factor. The capacities are listed in table 21.

TABLE 21

PERMISSIBLE PLANT CAPACITIES AT DIFFERENT STANDARDS
(MISSISSIPPI R.)

	PERMISSIBLE PLANT CAPACITY - FOSSIL (MW)		
Location River Mile	Existing	2°F Increment	4°F Increment
1150	336.6	480.8	624.9
1113	355.8	504.5	654.2
1076	396.4	562.2	684.4
1039	456.6	647.2	756.7
1001	513.9	728.7	907.7
964	540.7	767.6	1,037.4
700	3,407.2	4,531.9	6,800.4
599	3,371.6	5,201.3	7,500.2
500	4,984.2	7,251.8	9,551.7
399	5,927.5	8,592.5	11,301.8

The computations are based on the assumption that the permissible plants are fossil units operating with an overall efficiency of 36 percent and in-plant losses of 15 percent.

3. Influence of Capacity Factor. The effect of capacity factor on water consumption and cooling-related power production costs for various thermal standards is examined in this section. The determination of the influence of capacity factor (for capacity factors other than 80 percent) necessitates the repetition of the procedure developed in section III. A capacity factor of 70 percent is chosen since power plants normally operate with capacity factors in the range of 70 to 80 percent.

Clearly, it might be expected that annual cooling-related costs in mills/kW-hr will increase as capacity factor is decreased since there would be less energy produced. Also, it might be expected that the annual

water consumption at lower capacity factors would be less because there would be less heat rejected over the year.

These expectations are borne out in the water consumption and cost comparisons for the Upper Mississippi River as shown in table 22.

TABLE 22

COST AND WATER CONSUMPTION COMPARISONS FOR DIFFERENT CAPACITY FACTORS (MISSISSIPPI R.)

Thermal Standard	Annual Cost in mills/kW-hr		Annual Water Consumption ($10^6 m^3$)	
	80% CF	70% CF	80% CF	70% CF
Free Discharge	8.711	8.748	105.6	92.26
Existing	10.49	10.61	128.8	112.9
2°F Decrement	10.53	10.64	129.0	113.0
3°F Decrement	10.60	10.71	129.5	113.3
4°F Decrement	10.84	10.94	129.8	113.8
No Discharge	11.58	11.78	148.1	129.6

It is seen that the annual cost of all the thermal standards studied in mills/kW-hr is not very sensitive (of the order of 1 percent) to capacity factor. However, the annual water consumption is more sensitive to the capacity factor. For a 10 percent decrease in capacity factor, the water consumption is seen to decrease about 12 percent.

B. The Missouri River System. The Missouri River system originates near Three Forks in southwestern Montana at the confluence of the Jefferson, Gallatin, and Madison Rivers. The river flows generally northward from its origin, through the Middle and North Rock Mountains, and then follows an easterly course before entering the Great Plains, a typically smooth or rolling to somewhat hilly region. From the Montana-North Dakota border the river flows in a generally southeasterly direction to its confluence with the Mississippi River about 15 miles above St. Louis, Missouri. The total length of the Missouri River is about 2315 miles. The reaches considered in the calculation of the thermal regime are from the Fort Peck to the Garrison reservoir, from the Garrison to the Oahe reservoir, and from the Gavins Point reservoir to the southern Nebraska border. There are no power plants located along the reservoirs. The reservoir regulation and flow release schedules are prepared by the Research Control Center of the U.S. Army Corps of Engineers. The portion of the Missouri River between the Nebraska-Kansas state line (RM 490) and Fort Peck, Montana (RM 1763), lies in the Mid-Continent Area Power Pool geographical area, as shown in figure 2.

Monthly mean values of daily weather conditions were determined from data from seventeen first-order weather stations in the MAPP and adjacent areas. Summaries of the weather data for the stations were given in tables 7 through 10, and the locations of the weather stations are given by Paily et al. (1976). Average weather data for the 20-year period from 1953 to 1974 were used in the thermal regime analysis of the Missouri River.

Reservoir regulation has a major influence on the river flow of the Missouri River. The reservoir release from Gavins Point Dam varies from a minimum of 8,000 cfs in the nonnavigation season to more than 30,000 cfs during the navigation season. Monthly average values of daily discharges at nineteen gaging stations along the Missouri River were obtained from the U.S. Geological Survey Water Supply Papers and the U.S. Army Corps of Engineers reservoir release records. The data represent the averages for the 19-year period 1956 to 1974. A summary of the mean daily flow rates is given in table 23, which also includes the 7-day, 10-year low flows at the gaging stations after the regulation began. A map of the locations of the gaging stations is available elsewhere (Paily et al. 1976).

TABLE 23

SUMMARY OF MONTHLY MEAN VALUES OF
DAILY FLOW RATES -- MISSOURI RIVER

Gaging Station	River Mile	Mean of Daily Flow Rates in cfs					7-day, 10-yr. Low Flow	
		Averaging Period	Feb.	May	Aug.	Nov.	Period	Flow Rate (cfs)
Fort Peck	1763.5	1956-64	10775	8351	9028	8454	1935-77	720
Wolf Point	1701.4	1956-74	10890	9457	9160	8435	1929-77	1110
Culbertson	1620.8	1958-74	12015	10188	9169	8754	1944-78	1651.5
Williston	1552.7	1956-65	15127	23165	13295	13694	1957-65	7108.8
Garrison Dam	1389.9	1956-74	23959	21288	20617	21069	1950-68	5440
Bismark	1314.5	1956-74	24269	22152	21522	21722	1955-68	5580
Oahe Res. Rel	1073.2	1968-74	22157	27057	39683	33533	--	--
Big Bend Res. Rel	987.4	1968-74	22357	27086	39000	23600	--	--
Fort Randall	873.0	1956-74	9631	25673	33844	23420	--	--
Yankton	805.8	1956-74	12282	28368	34538	26065	1957-78	5551.9
Sioux City	732.3	1956-74	13668	31440	25129	27197	1957-71	5781
Omaha	615.9	1956-74	15160	34492	35728	25600	1957-71	4914
Nebraska City	562.6	1956-74	22272	42101	39494	34033	1957-71	6269
Rulo	498.0	1956-74	23910	45184	40843	35733	1957-71	6474

The temperature distributions in the Missouri River corresponding to average flow and weather conditions for the months of February, May, August, and November were determined using the steady-state ITRM. Stage versus width relationships for the river channel were obtained from the river cross-section tables and charts and corresponding water surface profiles furnished by the U.S. Army Corps of Engineers. The stage-discharge relationships for the various gaging stations were obtained from the U.S. Geological Survey. The top widths were adjusted according to flow rates using the stage-discharge relationships for the gaging stations and the stage-width relationships.

In the MAPP area, 10 power plants with a total of 24 units utilize the Missouri River water for once-through cooling. The details of the cooling systems of these plants are listed in table 24. The receiving water body for all plants listed in the table is the Missouri River, except for the Lewis & Clark plant which discharges into the Yellowstone River a short distance upstream of its confluence with the Missouri River. The sources and locations of industrial and municipal discharges that impose heat loads on the river are presented by Paily et al. (1976). The heat loads from the industrial and municipal sources generally are very small compared to the power plant loads and therefore are neglected in this study. Table 24 includes the proposed power plants along the Missouri River for which the type of cooling system has already been selected. The locations of the existing and proposed plants are shown in figure 3.

Economic data used in the outfitting and backfitting models are listed in previous sections. Monthly average wet- and dry-bulb temperatures for the Missouri River are given in table 25. Extreme and design wet- and dry-bulb temperatures are listed in table 26.

1. Water Consumption. Natural evaporation from the three study reaches of the Missouri River was calculated using the modified ITRM. To eliminate the effects of the natural variations in top widths along the river, the natural evaporation is divided by the river width to produce a unit natural evaporation. A plot of unit natural evaporation with distance downstream from Fort Peck Dam is shown in figure 8. Locations of U.S.

TABLE 24

SUMMARY OF EXISTING AND PROPOSED POWER PLANTS IN THE MAPP REGION OF THE MISSOURI RIVER BASIN

PLANT			LOCATION		INSTALLATION			CONDENSER FLOW	
Utility	Name	Code*	City/County and State	River Mile	Tot. Cap. (MWe)	Efficiency	No. of Units	Quantity (cfs)	Temp. Rise (°F)
MDU	Lewis & Clark	FOBE	Sidney, Mont.	1579	50	.325	1	49	25
BEPC	Leland Olds #1	FOBE	Stanton, N.D.	1380	217	.365	1	162.64	27
BEPC	Leland Olds #2	FOAE	Stanton, N.D.	1380	438	.356	1	396.6	25
UPA	Stanton	FOBE	Stanton, N.D.	1380	172	.362	1	220	16
MDU	R.M. Heskett #1,2	FOBE	Mandan, N.D.	1320	100	.309	2	91	26.9
IPS	George Neal #1,2	FOBE	Salix, Ia.	731	496	.394	2	425.4	20.51
IPS	George Neal #3,4	FOAP	Salix, Ia.	731	1096	.344	2	1359	18
OPPD	Fort Calhoun	NOBE	Washington, Neb.	639	475	.345	1	701.8	18
OPPD	North Omaha #1-5	FOBE	Omaha, Neb.	616	646	.359	5	797.8	16.8
IPL	Council Bluffs #1,2	FOBE	Council Bluffs, Ia.	616	138	.346	2	183.09	16.68

TABLE 24 (CONTINUED)

PLANT			LOCATION			INSTALLATION		CONDENSER FLOW	
Utility	Name	Code*	City/County and State	River Mile	Tot. Cap. (MWe)	Efficiency	No. of Units	Quantity (cfs)	Temp. Rise (°F)
IPL	Council Bluffs #3	FOAP	Council Bluffs, Ia.	616	650	.308	1	957	18.2
OPPD	Jones Street #11,12	FOBE	Omaha, Neb.	616	83	.316	2	138.3	15.4
NPPD	Kramer #1-3	FOBE	Bellevue, Neb.	602	113	.306	3	306	10
OPPD	Nebraska City	FOAP	Nebraska City, Neb.	561	575	.348	1	700	18
NPPD	Cooper	NOBE	Brownville, Neb.	533	836	.310	1	1455	18

* F = Fossil, N = Nuclear, O = Once-through, W = Wet cooling tower, S = Spray canal, A = turbine A, B = turbine B, E = Existing plant, P = Proposed plant

TABLE 25

MONTHLY AVERAGE WET AND DRY BULB TEMPERATURES (MISSOURI R.)

Power Plant Location	WET BULB TEMP., °F				DRY BULB TEMP., °F			
	Feb.	May	Aug.	Nov.	Feb.	May	Aug.	Nov.
Sidney, Mont.	13.0	46.1	58.3	25.5	14.8	54.5	69.6	28.1
Stanton, N.D.	12.2	47.0	58.7	25.2	14.0	54.6	69.6	28.5
Mandan, N.D.	12.2	47.0	58.7	25.2	14.0	54.6	69.6	28.6
Salix, Ia.	20.8	54.1	66.5	33.3	23.0	61.7	73.1	36.9
Washington, Neb.	23.6	55.4	70.2	35.3	26.2	62.9	74.8	39.1
Omaha, Neb.	24.3	55.7	68.1	35.7	29.7	63.2	75.2	39.7
Council Bluffs, Ia.	24.3	55.7	68.1	35.7	29.7	63.2	75.2	39.7
Nebraska City, Neb.	25.4	56.0	68.6	36.7	28.4	63.9	75.5	40.7
Brownville, Neb.	26.0	56.2	68.9	37.1	29.2	64.3	75.7	41.2

TABLE 26

DESIGN AND EXTREME WET AND DRY BULB TEMPERATURES (MISSOURI R.)

LOCATION		DRY BULB TEMP., °F		WET BULB TEMP., °F	
City/County and State	River Mile	Design	Extreme	Design	Extreme
Sidney, Mont.	1579	89.00	96.00	65.00	70.00
Stanton, N.D.	1380	85.10	90.10	68.70	73.70
Mandan, N.D.	1320	84.00	89.00	68.00	73.00
Salix, Ia.	731	82.49	89.02	68.20	80.73
Washington, Neb.	639	82.33	90.60	74.05	79.33
Omaha, Neb.	616	83.95	9.100	69.84	79.00
Council Bluffs, Ia.	602	84.12	91.23	70.04	78.79
Nebraska City, Neb.	561	84.63	92.02	70.72	78.10
Brownville, Neb.	533	84.98	92.42	71.07	77.75

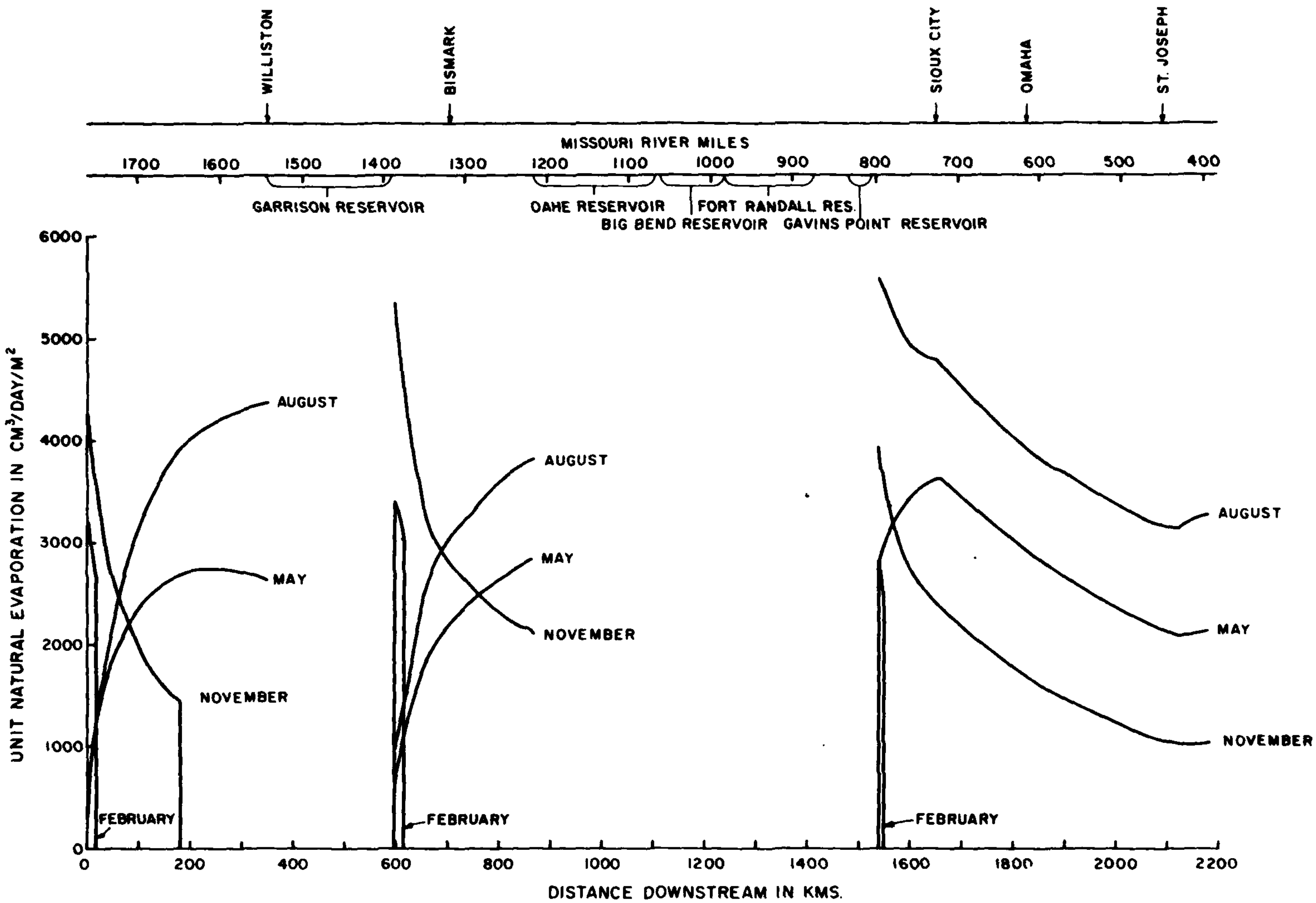

Figure 8. Unit natural evaporation along the Missouri River

Weather Bureau stations from which meteorologic data were obtained are indicated along the top of the figure. Also shown on the top scale of the figure are the locations of the five storage reservoirs for which computations were not made. Sharp declines and rises in the unit natural evaporation rates are primarily due to the reservoir-release temperatures which tend to be low in the summer and high in the winter due to density stratification. These temperatures are "artificial" temperatures and as such, are not sustained over any length of the river by the prevailing hydrologic and meteorologic conditions. Unit natural evaporation for the month of February is zero in all of the reaches except where reservoir release temperatures raise the river temperature above freezing.

To determine the effects of heated effluents on the natural evaporation of the river, the unit evaporation was computed, and the unit natural evaporation was subtracted to produce unit net evaporation. Unit net evaporation is the evaporation due to the presence of heat loads on the river. Unit net evaporation is shown as a function of distance downstream for the month of August in figure 9. The distributions of unit net evaporation for the months of May and November are not shown because they are similar to the distribution for August conditions. Locations of the power plants are shown at the top of the figure. The peaks in the unit net evaporation curves occur at power-plant discharge locations followed by regions where the temperature and, hence, the evaporation decays as the heat is dissipated.

Unit net evaporation for the month of February is shown in figure 10. Evaporation due to heated effluents for the months of August and February were chosen because extreme meteorologic and hydrologic conditions usually occur during these months. The unit net evaporation for February is zero for several reaches of the river. In comparison with February conditions for the Mississippi River, the evaporation is sustained over greater distances, particularly in the third reach. The proximity of power plants on the third reach of the Missouri River combined with the smaller flow rate and width of the Missouri River make it easier for thermal discharges to keep the river temperature above freezing thereby decreasing ice cover. Abrupt spikes and sudden peaks in the curves occur at locations of power plant discharges. The magnitude of the unit net evaporation is higher in February

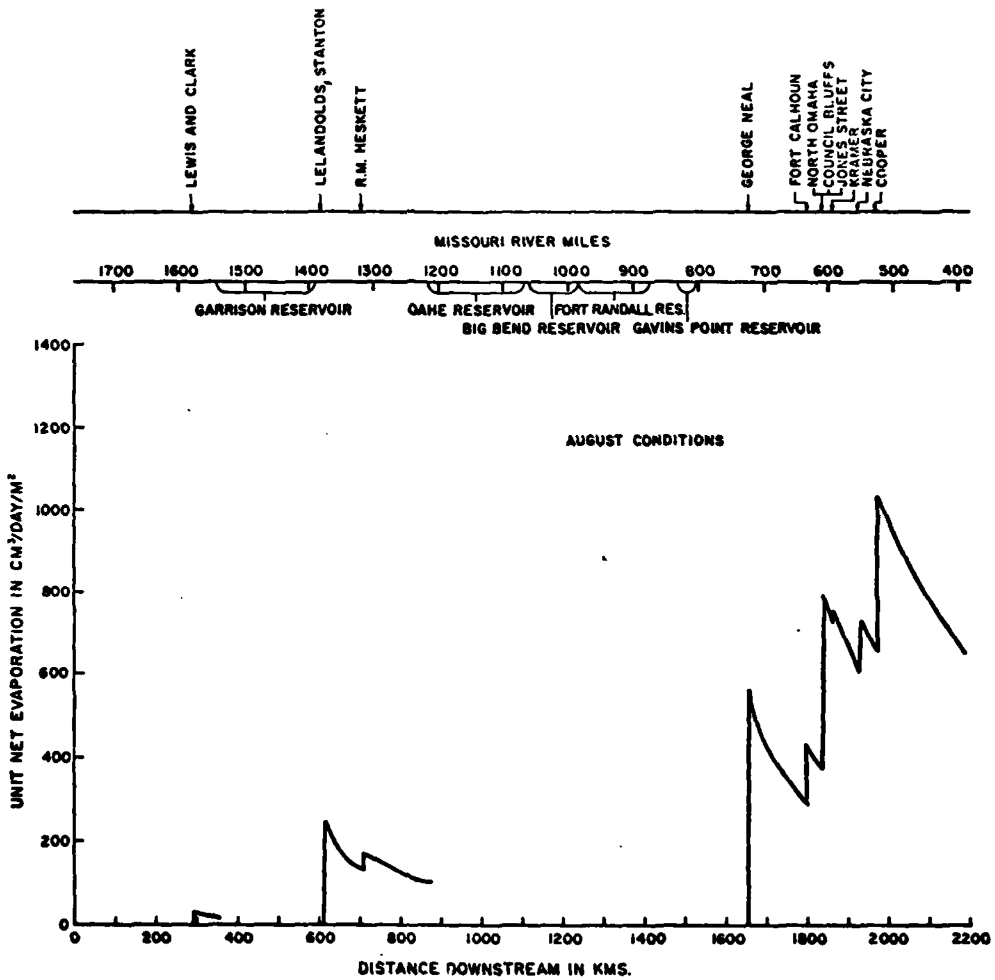

Figure 9. Unit net evaporation for August along the Missouri River

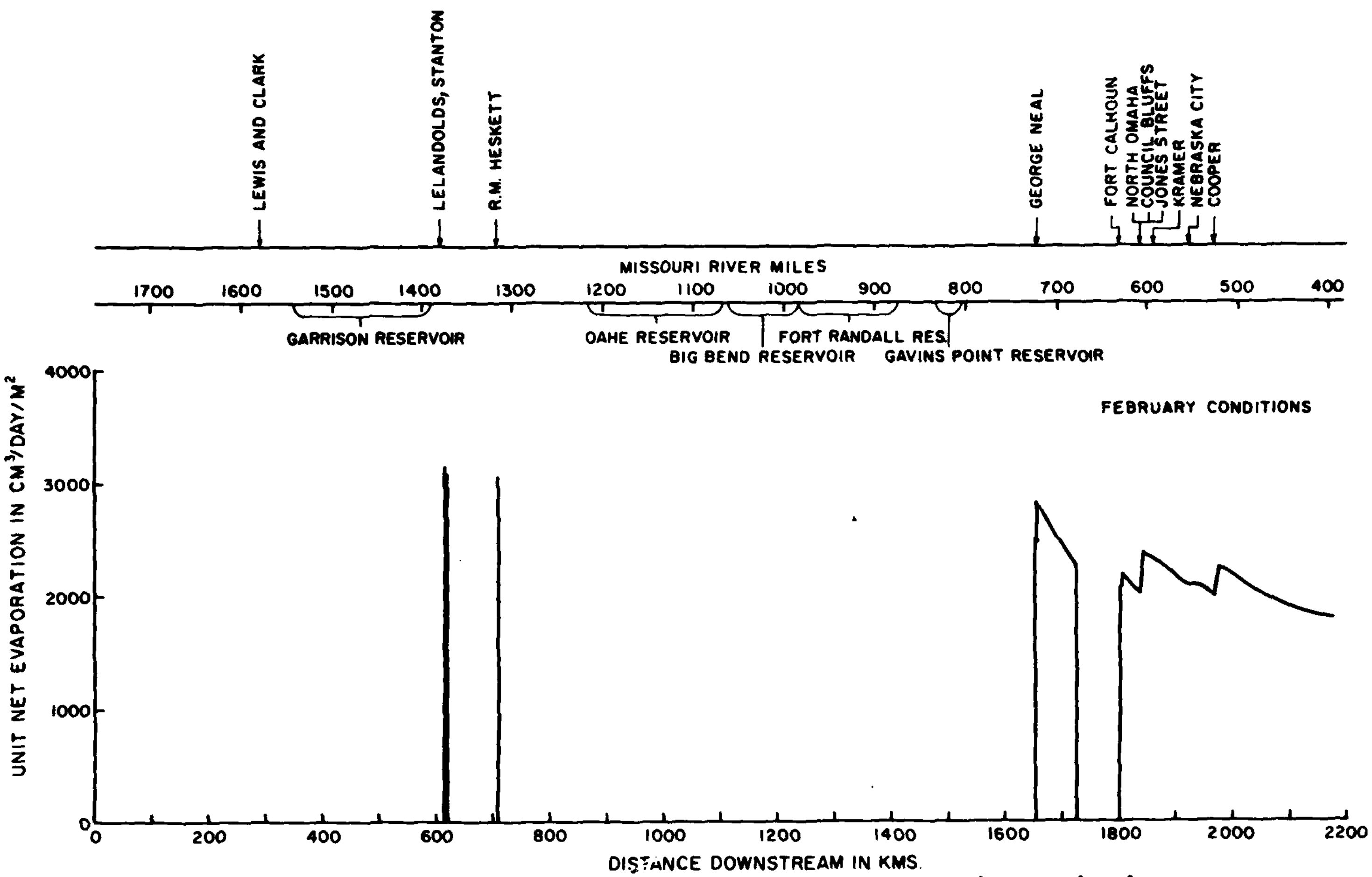

Figure 10. Unit net evaporation for February along the Missouri River

than in August. This increase is primarily due to the existing heat loads which keep a large portion of the river free of ice cover resulting in additional heat input from the atmosphere in the form of solar and atmospheric radiation.

All power plants on the Missouri River use the once-through cooling mode at existing thermal standards. Therefore, water consumption for the existing thermal standard is the same as that for the free-discharge standard. By integrating the net river evaporation along the river and over the year and computing the total evaporation from wet cooling towers, the total annual evaporation for various thermal standards were computed. Table 27 lists the total annual evaporation for the existing and no-discharge thermal standards, and also for the 2°F, 3°F, and 4°F decrement thermal standards.

TABLE 27

WATER CONSUMPTION OF DIFFERENT THERMAL STANDARDS (MISSOURI R.)

Thermal Standard	Net Annual Evaporation from River surface $10^6 m^3$	Annual Water Consumption of Wet Towers $10^6 m^3$	Total Annual Evaporation $10^6 m^3$
Existing	61.35	0	61.35
2°F Decrement	61.35	0	61.35
3°F Decrement	60.42	1.545	61.97
4°F Decrement	29.95	32.64	62.59
No Discharge	0	67.78	67.78

It is seen from this table that the no-discharge thermal standard represents an annual increase of 6.4 million m^3 over the existing or free-discharge condition (an increase of 10.5 percent). There is no significant increase in water consumption at the 2°F and 3°F decrement thermal standards. Notice, however, that at the 4°F decrement standard, thermal exceedances occur under average flow at a number of plants, causing them to adopt hybrid cooling systems thereby increasing total water consumption because of the increased cooling tower operation.

Net annual evaporation from the river water surface listed in table 27 for various thermal standards is obtained by summing net evaporation

along the reaches shown in figures 9 and 10 and downstream until the effects of power plant discharges become negligible. The net annual evaporation from the river surface is therefore the total annual consumptive use of water resulting from the operation of power plants employing once-through cooling. The total natural evaporation is computed only along the study reach. Care should be taken when comparing the net annual evaporation shown in table 27 with the total annual natural evaporation of 253 million m^3.

Water consumption along the study reaches on the Missouri River is about half that obtained for the Upper Mississippi River because there are fewer power plants on the Missouri River. Also, the percentage increase in water consumption over the existing standards case as a result of backfitting/outfitting all power plants with closed-cycle cooling systems is lower than that for the Upper Mississippi River. This difference might be attributed to the larger net evaporation from the Missouri River in proportion to the heat rejected to the river; in particular, the large net evaporation rates during February as a result of extensive break-up of ice-cover along the Missouri River is the major cause.

2. Economic Costs. Costs for the free-discharge thermal standard are presented in table 28. These computed results indicate that the average cooling-related cost of power production on the Missouri River with a free-discharge thermal standard is 10.03 mills/kW-hr.

Costs of various thermal standards are computed with the backfitting and outfitting models for each power plant identified by the ITRM as requiring auxiliary cooling for the particular standard under consideration. Costs of existing thermal standards are given in table 29. The average cooling related cost of power production on the Missouri River is of the order of 10.48 mills/kW-hr for the present thermal standards, an increase of 0.45 mills/kW-hr over the free-discharge condition (an increase of 4.5 percent). The value of 0.45 mills/kW-hr represents the average "cost" of existing thermal standards on the Missouri River.

The no-discharge thermal standard involves additional costs incurred as a result of backfitting once-through cooling systems with cooling towers. Costs of the no-discharge thermal standard are listed in table 30. The no-discharge thermal standard represents an average increase

TABLE 28

COMPUTED COSTS OF FREE-DISCHARGE THERMAL STANDARD (MISSOURI R.)

Plant & Unit No.	Location (RM)	Capacity (MW)	Code*	Capital Cost (millions of dollars)	Annual Operating Costs (millions of dollars)	Total Annual Cost (millions of dollars)	Costs (mills/kW-hr)
Lewis & Clark	1579	50	FOBE	0.559	4.307	4.389	12.53
Leland Olds #1	1380	217	FOBE	1.902	16.69	16.97	11.16
Leland Olds #2	1380	438	FOAE	4.217	34.47	35.09	11.43
Stanton	1380	172	FOBE	1.636	13.32	13.56	11.25
R.M. Heskett #1,2	1320	100	FOBE	1.156	9.088	9.259	13.21
George Neal #1,2	731	496	FOBE	4.560	35.28	35.95	10.34
George Neal #3,4	731	1096	FOAP	13.96	89.25	91.31	11.89
Fort Calhoun	639	475	NOBE	7.216	9.656	10.72	3.220
North Omaha #1-5	616	646	FOBE	8.018	50.50	51.68	11.42
Council Bluffs #1,2	616	138	FOBE	1.835	11.18	11.45	11.84
Council Bluffs #3	616	650	FOAP	9.870	59.22	60.68	13.32
Jones Street #11,12	616	83	FOBE	1.350	7.361	7.560	13.00
Kramer #1,2,3	602	113	FOBE	2.584	10.35	10.73	13.55
Nebraska City	561	575	FOAP	7.197	46.36	47.42	11.77
Cooper	533	836	NOBE	14.95	18.86	21.07	3.600
TOTAL		6085				427.8	10.03

* F = Fossil, N = Nuclear, O = Once-through, W = Wet cooling tower, S = Spray canal, A = turbine A, B = turbine B, E = Existing plant, P = Proposed plant

TABLE 29

COMPUTED COSTS OF EXISTING THERMAL STANDARDS (MISSOURI R.)

Plant & Unit No.	Location (RM)	Capacity (MW)	Code*	Capital Cost (millions of dollars)	Annual Operating Costs (millions of dollars)	Total Annual Cost (millions of dollars)	Costs (mills/kW-hr)
Lewis & Clark	1579	50	FOBE	0.559	4.307	4.389	12.53
Leland Olds #1	1380	217	FOBE	1.902	16.69	16.97	11.16
Leland Olds #2	1380	438	FOAE	4.217	34.47	35.09	11.43
Stanton	1380	172	FOBE	1.636	13.32	13.56	11.25
R.M. Heskett	1320	100	FOBE	1.157	9.088	9.259	13.21
George Neal #1,2	731	496	FOBE	4.560	35.28	35.95	10.34
George Neal #3,4	731	1096	FOAP	13.96	89.25	91.31	11.89
Fort Calhoun	639	475	NOBE	7.216	9.656	10.72	3.220
North Omaha #1-5	616	646	FOBE	35.05	50.50	56.52	12.48
Council Bluffs #1,2	616	138	FOBE	8.814	11.18	12.70	13.13
Council Bluffs #3	616	650	FOAP	20.00	59.22	62.17	13.65
Jones Street #11,12	616	83	FOBE	6.227	7.361	8.433	14.50
Kramer #1,2,3	602	113	FOBE	11.78	10.35	12.38	15.63
Nebraska City	561	575	FOAP	7.197	46.36	47.42	11.77
Cooper	533	836	NOBE	65.80	18.86	30.17	5.149
TOTAL						447.0	10.48

* F = Fossil, N = Nuclear, O = Once-through, W = Wet cooling tower, S = Spray canal, A = turbine A, B = turbine B, E = Existing plant, P = Proposed plant

TABLE 30

COMPUTED COSTS OF NO-DISCHARGE THERMAL STANDARD (MISSOURI R.)

Plant & Unit No.	Location (RM)	Capacity (MW)	Code*	Capital Cost (millions of dollars)	Annual Operating Costs (millions of dollars)	Total Annual Cost (millions of dollars)	Costs (mills/kW-hr)
Lewis & Clark	1579	50	FOBE	4.398	5.045	5.815	16.59
Leland Olds #1	1380	217	FOBE	19.14	19.29	22.66	14.90
Leland Olds #2	1380	438	FOAE	14.82	37.92	40.44	13.17
Stanton	1380	172	FOBE	11.57	14.89	16.91	14.03
R.M. Heskett #1,2	1320	100	FOBE	9.754	10.67	12.38	17.66
George Neal #1,2	731	496	FOBE	34.25	39.97	45.96	13.22
George Neal #3,4	731	1096	FOAP	35.07	98.81	104.0	13.54
Fort Calhoun	639	475	NOBE	48.01	16.29	24.66	7.407
North Omaha #1-5	616	646	FOBE	48.11	57.89	66.25	14.63
Council Bluffs #1,2	616	138	FOBE	11.26	12.85	14.81	15.31
Council Bluffs #3	616	650	FOAP	24.95	66.18	69.86	15.34
Jones Street #11,12	616	83	FOBE	8.590	8.477	9.972	17.14
Kramer #1,2,3	602	113	FOBE	11.78	11.83	13.86	17.50
Nebraska City	561	575	FOAP	17.56	51.83	54.75	13.59
Cooper	533	836	NOBE	94.40	32.75	49.17	8.394
TOTAL		6085				551.5	12.93

* F = Fossil, N = Nuclear, O = Once-through, W = Wet cooling tower, S = Spray canal, A = turbine A, B = turbine B, E = Existing plant, P = Proposed plant

TABLE 31

REGIONAL COST COMPARISONS OF DIFFERENT THERMAL STANDARDS (MISSOURI R.)

Thermal Standard	Total Costs		Incremental Cost of Standard above Free-Discharge	
	Annual 10^6 dollars	mills/kW-hr	Annual 10^6 dollars	mills/kW-hr
Free Discharge	427.8	10.03		
Existing	447.0	10.48	19.2	0.45
2°F Decrement	464.0	10.88	36.2	0.85
3°F Decrement	475.1	11.14	47.3	1.11
4°F Decrement	511.9	12.00	84.1	1.97
No Discharge	551.5	12.93	123.7	2.90

of 2.45 mills/kW-hr over the existing average annual costs (an increase of 23.4 percent). The "cost" of the no-discharge thermal standard is of the order of 2.90 mills/kW-hr more than the free-discharge condition (an increase of 28.9 percent). Table 31 lists regional cost figures for various thermal standards. It is interesting to note that the total costs in mills/kW-hr for the various thermal standards on the Missouri River shown in table 31 are less than the corresponding costs on the Mississippi River. This difference is due to the greater ratio of fossil-fueled power to total power generation on the Missouri River which increases the total costs.

For the Missouri River, existing thermal standards are exceeded at North Omaha, Council Bluffs, Jones Street, Kramer, Nebraska City, and Cooper power plants during low-flow conditions. Capital costs of towers are included in the costs at these plants for existing thermal standards. The no-discharge thermal standard produces additional costs in terms of energy losses. The total annual energy loss which would occur at the no-discharge thermal standard is 1,042 million kW-hr or 119 MW. This energy loss represents the amount of energy that must be purchased from other utilities.

Thermal standards more relaxed than existing are also examined along the Missouri River. Again, 2°F and 4°F increases above existing

allowable temperature rises are considered.

Permissible plant capacities along the Missouri River at the existing and the 2°F and 4°F increment thermal standards under average flow conditions are shown in table 32. As might be expected, there is considerably more power generation capacity at the relaxed standards.

TABLE 32

PERMISSIBLE PLANT CAPACITIES AT DIFFERENT STANDARDS (MISSOURI R.)

	PERMISSIBLE PLANT CAPACITY - FOSSIL (MW)		
Location River Mile	Existing	2°F Increment	4°F Increment
1736	408.4	1,225.3	2,042.1
1649	258.9	783.9	1,318.5
1543	3,068.0	4,122.7	5,181.1
1314	4,781.8	6,863.3	8,944.7
1252	1,349.1	1,931.3	2,534.0
492	4,875.6	7,207.5	9,500.5

3. Influence of Capacity Factor. The effects of capacity factor on water consumption and cooling-related costs along the Missouri River is shown in table 33. It is seen that the magnitude of the plant capacity factor affects the cooling cost and water consumption in the same manner as along the Mississippi River, i.e., a capacity factor change from 80 percent to 70 percent causes a cost increase of about 1 percent and a water consumption decrease of about 12 percent.

TABLE 33

COST AND WATER CONSUMPTION COMPARISONS
FOR DIFFERENT CAPACITY FACTORS (MISSOURI R.)

Thermal Standard	Annual Cost in mills/kW-hr		Annual Water Consumption ($10^6 m^3$)	
	80% CF	70% CF	80% CF	70% CF
Free Discharge	10.03	10.07		
Existing	10.48	10.59	61.35	53.52
2°F Decrement	10.88	10.97	61.35	53.52
3°F Decrement	11.14	11.24	61.97	53.53
4°F Decrement	12.00	12.08	62.59	55.83
No Discharge	12.93	13.14	67.78	59.31

V. DISCUSSION AND CONCLUDING REMARKS

Environmental objective functions are difficult to define due to the incommensurable nature of the benefits derived from fish and wildlife preservation, aesthetics, etc., in comparison with benefits that can easily be measured in economic terms. Impacts of thermal discharges on streams can be measured in terms of temperature distributions, dissolved oxygen, eutrophication, etc. Biological data can be used to determine tolerance levels for various species of fish. Combinations of these two data sources will result in cause-effect relationships whereby certain maximum temperatures or temperature increases can be related to the number of fish adversely affected. However, the value of preserving fish and wildlife is an incommensurable benefit in that it cannot be easily quantified in dollar terms. As a result, the value of preserving the aquatic-life environment takes on a qualitative character in the determination of the costs and benefits of energy production.

The effects on fish and wildlife as a result of thermal discharges from power plants is often termed a technological external cost/benefit. The external costs/benefits representing changes in social welfare cannot easily be priced and are produced incidental to the purpose of power production. Since the external costs/benefits of heated discharges can seldom be valued or quantified in terms appropriate for comparison, the decision maker must weigh them politically. The decision problem is so overwhelming that our political leaders must rely heavily on identification by analysts of the environmental consequences and associated costs of conservation. Here the question is one of perception and of proper identification and measurement of long-term biological and economic effects.

A decision maker who is aware of the environmental ramifications of thermal standards can determine future thermal standards at least partly on the basis of the costs incurred in meeting those standards. The question then becomes not how much are fish and wildlife worth, but how much is the public willing to pay for increasing environmental benefit. One way of presenting the costs of thermal standards is in the form of trade-off relationships which depict the costs of meeting various thermal regulations.

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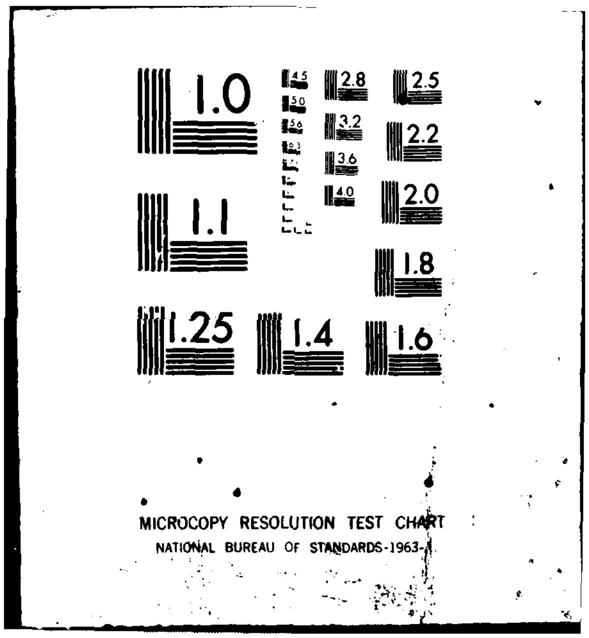
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Summaries of marginal trade-off relationships for the reaches of the Mississippi and Missouri Rivers considered in this study are shown in tables 34 and 35, respectively. It can be seen from these tables that annual economic costs and water consumption increase when thermal regulations become more restrictive.

TABLE 34

MARGINAL TRADE-OFF RELATIONSHIPS (MISSISSIPPI R.)

Thermal Standard	Incremental "cost" over Free-Discharge Thermal Standard		
	Annual Economic Cost		Annual Evaporation
	10^6 dollars	mills/kW-hr	million m^3
Existing	153.9	1.78	23.2
2°F Decrement	157.8	1.82	23.4
3°F Decrement	164.0	1.89	23.9
4°F Decrement	184.5	2.13	24.2
No Discharge	248.2	2.87	42.5

TABLE 35

MARGINAL TRADE-OFF RELATIONSHIPS (MISSOURI R.)

Thermal Standard	Incremental "cost" over Free-Discharge Thermal Standard		
	Annual Economic Cost		Annual Evaporation
	10^6 dollars	mills/kW-hr	million m^3
Existing	19.2	0.45	0
2°F Decrement	36.2	0.85	0
3°F Decrement	47.3	1.11	0.62
4°F Decrement	84.1	1.97	1.24
No Discharge	123.7	2.90	6.43

Comparison of the two tables show that the economic cost of the no-discharge standard is about the same for both rivers in mills/kW-hr. However, the incremental cost of the no-discharge over the existing standard along the Missouri River is more than twice the incremental cost along the Mississippi River. This difference occurs because at the existing standard, all plants on the Missouri River employ once-through cooling, which is not

the case on the Mississippi River. The same reason can also be attributed to the steeper increase in costs on the Missouri River as thermal standards are made more restrictive. Marginal water consumption on the Mississippi River is larger because 1) there are more plants and therefore larger capacity along the Mississippi River; 2) the ratio of nuclear to total power generation is higher along the Mississippi River; 3) there is, in proportion to the heat rejection, a greater net evaporation from the surface of the Missouri River which reduces the marginal increases in water consumption as plants adopt hybrid or closed-cycle cooling systems.

A visual representation of the marginal cost trade-offs for the two rivers is shown in figure 11. Comparisons of water consumption of different thermal standards also are given in table 16 for the Mississippi River and table 27 for the Missouri River. Cost comparisons for the two rivers also are given in tables 20 and 31, respectively.

Determining future thermal standards will be a difficult problem for decision makers. However, if the costs of providing different levels of environmental protection are considered along with a complete analysis of the benefits that would accompany different thermal criteria, the task of setting new regulations becomes a cost-benefit problem. The trade-off relations of this study can be used to assess the costs of remaining at the existing thermal standards or moving to more restrictive thermal standards. The decision maker must examine the benefits of stricter thermal standards and the costs that would result from these regulations and decide if the benefits outweigh the costs.

Future thermal standards should be considered with full knowledge of the trade-offs in terms of economic and environmental concerns. The inability of analysts to present these concerns in commensurable units places a heavier burden on the decision maker. However, the analyst must provide a complete measure of the effects in whatever quantitative units are available. Complete environmental impact statements should be made in terms of tolerable temperature gradients or maximums related to survival of marine life. An assessment of economic costs consequent to various thermal standards then becomes a key part in the decision making process. Without full representation

of the real costs, the planner has little hope of determining society's desired balance between environmental protection and energy production costs.

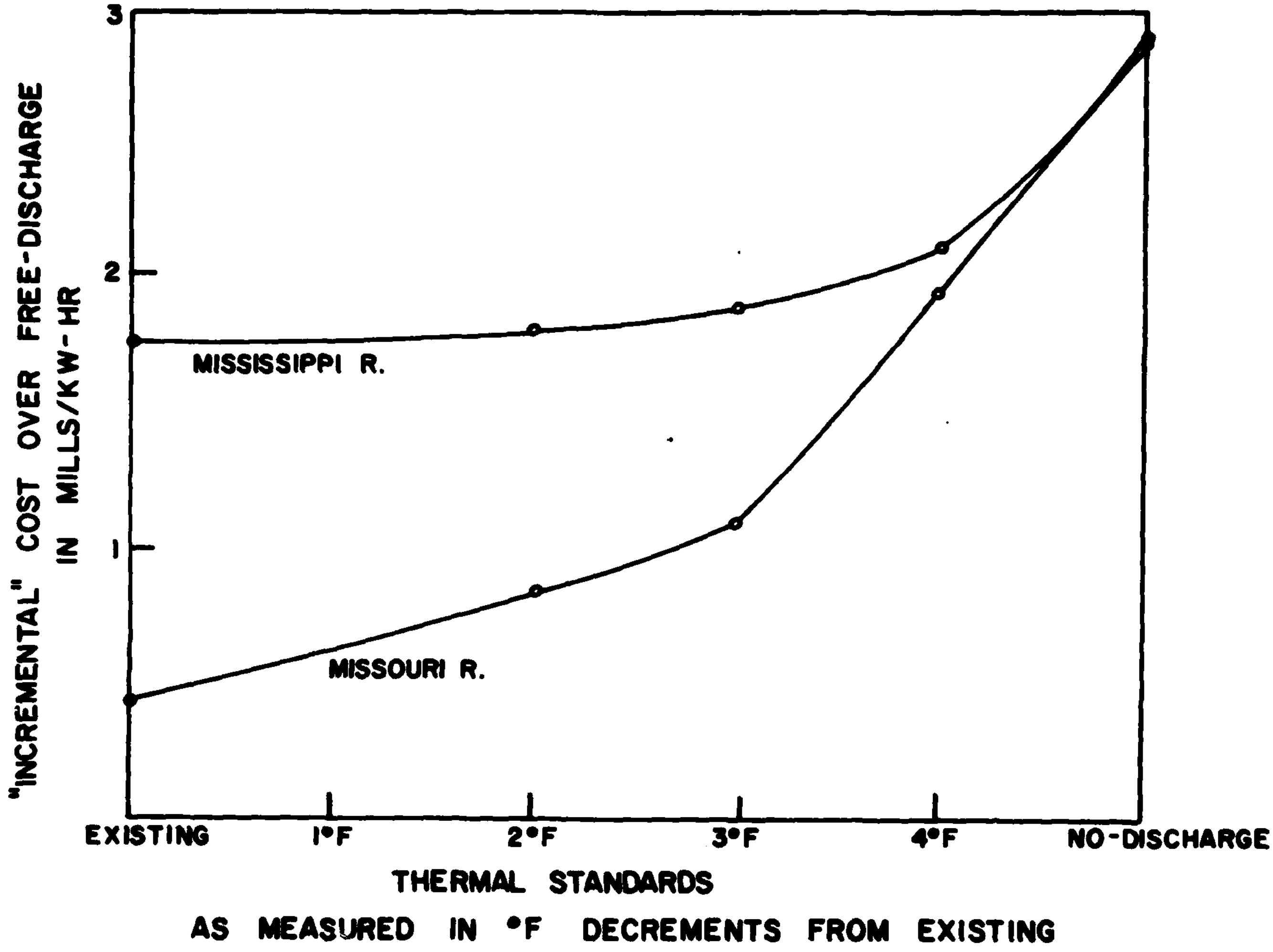

Figure 11. Incremental cost trade-offs

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